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ENCYCLOPEDIA OF EARTH & SPACE SCIENCE

TIMOTHY KUSKY, PH.D.

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For Daniel and Shoshana

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INTRODUCTION

Encyclopedia of Earth and Space Science is a two-volume reference intended to complement the material typically taught in high school Earth science and astronomy classes, and in introductory college geology, atmospheric sciences, and astrophysics courses. The substance reflects the fundamental concepts and principles that underlie the content standards for Earth and space science identified by the National Committee on Science Education Standards and Assessment of the National Research Council for grades 9–12. Within the category of Earth and space science, these include energy in the Earth system, geochemical cycles, origin and evolution of the Earth system, and origin and evolution of the universe. The National Science Education Standards (NSES) also place importance on student awareness of the nature of science and the process by which modern scientists gather information. To assist educators in achieving this goal, other subject matter discusses concepts that unify the Earth and space sciences with physical science and life science: science as inquiry, technology and other applications of scientific advances, science in personal and social perspectives including topics such as natural hazards and global challenges, and the history and nature of science. A listing of entry topics organized by the relevant NSES Content Standards and an extensive index will assist educators, students, and other readers in locating information or examples of topics that fulfill a particular aspect of their curriculum.

Encyclopedia of Earth and Space Science emphasizes physical processes involved in the formation and evolution of the Earth and universe, describes many examples of different types of geological and astrophysical phenomena, provides historical perspectives, and gives insight into the process of scientific inquiry by incorporating biographical profiles of people who have contributed significantly to the development of the sciences. The complex processes related to the expansion of the universe from the big bang are presented along with an evaluation of the physical principles and fundamental laws that describe these processes. The resulting structure of the universe, galaxies, solar system, planets, and places on the Earth are all discussed, covering many different scales of observation from the entire universe to the smallest subatomic particles. The geological characteristics and history of all of the continents and details of a few selected important areas are presented, along with maps, photographs, and anecdotal accounts of how the natural geologic history has influenced people. Other entries summarize the major branches and subdisciplines of Earth and space science or describe selected applications of the information and technology gleaned from Earth and space science research.

The majority of this encyclopedia comprises 250 entries covering NSES concepts and topics, theories, subdisciplines, biographies of people who have made significant contributions to the earth and space sciences, common methods, and techniques relevant to modern science. Entries average more than 2,000 words each (some are shorter, some longer), and most include a cross-referencing of related entries and a selection of recommended further readings. In addition, one dozen special essays covering a variety of subjects—especially how different aspects of earth and space sciences have affected people—are placed along with related entries. More than 300 color photographs and line art illustrations, including more than two dozen tables and charts, accompany the text, depicting difficult concepts, clarifying complex processes, and summarizing information for the reader. A glossary defines relevant scientific terminology. The back matter of *Encyclopedia of Earth and Space Science* contains a geological timescale, tables of conversion between different units used in the text, and the periodic table of the elements.

I have been involved in research and teaching for more than two decades. I am honored to be a Distinguished Professor and Yangtze Scholar at China's leading geological institution, China University of Geosciences, in Wuhan. I was formerly the P. C. Reinert Endowed Professor of Natural Sciences and am the founding director of the Center for Environmental Sciences at St. Louis University. I am actively involved in research, writing, teaching, and advising students.

My research and teaching focus on the fields of plate tectonics and the early history of the Earth, as well as on natural hazards and disasters, satellite imagery, mineral and water resources, and relationships between humans and the natural environment. I have worked extensively in North America, Asia, Africa, Europe, the Middle East, and the rims of the Indian and Pacific Oceans. During this time I have authored more than 25 books, 600 research papers, and numerous public interest articles, interviews with the media (newspapers, international, national and local television, radio, and international news magazines), and I regularly give public presentations on science and society. Some specific areas of current interest include the following:

- Precambrian crustal evolution
- tectonics of convergent margins
- natural disasters: hurricanes, earthquakes, volcanoes, tsunami, floods, etc.
- drought and desertification
- Africa, Madagascar, China
- Middle East geology, water, and tectonics

I received bachelor and master of science degrees from the Department of Geological Sciences at the State University of New York at Albany in 1982 and 1985, respectively, then continued my studies in earth and planetary sciences at the Johns Hopkins University in Baltimore. There I received a master of arts in 1988 and a Ph.D. in 1990. During this time I was also a graduate student researcher at the NASA Laboratory for Terrestrial Physics, Goddard Space Flight Center. After this I moved to the University of California at Santa Barbara where I did postdoctoral research in Earth-Sun-Moon dynamics in the Department of Mechanical Engineering. I then moved to the University of Houston for a visiting faculty position in the department of geosciences and allied geophysical laboratories at the University of Houston. In 1992 I moved to a research professor position in the Center for Remote Sensing at Boston University and also took a part-time appointment as a research geologist with the U.S. Geological Survey. In 2000 I moved to St. Louis University, then was appointed to a distinguished professor position at China University of Geoscience in 2009.

I have tried to translate as much of this experience and knowledge as possible into this two-volume encyclopedia. It is my hope that you can gain an appreciation for the complexity and beauty in the earth and space sciences from different entries in this book, and that you can feel the sense of exploring, learning, and discovery that I felt during the research related here, and that you enjoy reading the different entries as much as I enjoyed writing them for you.

Entries Categorized by National Science Education Standards for Content (Grades 9–12)

When relevant an entry may be listed under more than one category. For example, Alfred Wegener, one of the founders of plate tectonic theory, is listed under both Earth and Space Science Content Standard D: Origin and Evolution of the Earth System, and Content Standard D: History and Nature of Science. Subdisciplines are listed separately under the category Subdisciplines, which is not a NSES category, but are also listed under the related content standard category.

Science as Inquiry (Content Standard A)

astronomy
astrophysics
biosphere
climate
climate change
Coriolis effect
cosmic microwave background radiation
cosmology
Darwin, Charles
ecosystem
Einstein, Albert
environmental geology
evolution
Gaia hypothesis
geological hazards
global warming
greenhouse effect
hydrocarbons and fossil fuels
ice ages
life's origins and early evolution
mass extinctions
origin and evolution of the Earth and solar system
origin and evolution of the universe
ozone hole
plate tectonics
radiation
sea-level rise

Earth and Space Science (Content Standard D): Energy in the Earth System

asthenosphere
atmosphere
aurora, aurora borealis, aurora australis
black smoker chimneys
climate
climate change
clouds
convection and the Earth's mantle
Coriolis effect
cosmic microwave background radiation
cosmic rays
Earth
earthquakes
Einstein, Albert
El Niño and the Southern Oscillation (ENSO)
electromagnetic spectrum
energy in the Earth system
Gaia hypothesis
geodynamics
geological hazards
geomagnetism, geomagnetic reversal
geyser
global warming
greenhouse effect
hot spot
hurricanes
ice ages
large igneous provinces, flood basalt
magnetic field, magnetosphere
mantle plumes
mass wasting
meteorology
Milankovitch cycles
monsoons, trade winds
ocean currents
paleomagnetism
photosynthesis
plate tectonics
precipitation
radiation
radioactive decay
subduction, subduction zone
Sun
thermodynamics
thermohaline circulation
thunderstorms, tornadoes
tsunami, generation mechanisms
volcano

Earth and Space Science (Content Standard D): Geochemical Cycles

asthenosphere
atmosphere
biosphere
black smoker chimneys
carbon cycle
climate change
clouds
continental crust
convection and the Earth's mantle
crust
diagenesis
Earth
economic geology
ecosystem
environmental geology
erosion
Gaia hypothesis
geochemical cycles
global warming
granite, granite batholith
groundwater
hydrocarbons and fossil fuels
hydrosphere
igneous rocks
large igneous provinces, flood basalt
lava
lithosphere
magma
mantle
mantle plumes
metamorphism and metamorphic rocks
metasomatic
meteoric
ocean currents
ophiolites
ozone hole
petroleum geology
photosynthesis
plate tectonics
precipitation
river system
seawater
sedimentary rock, sedimentation
soils
subduction, subduction zone
thermodynamics
thermohaline circulation
thunderstorms, tornadoes
volcano
weathering

Earth and Space Science (Content Standard D): Origin and Evolution of the Earth System

accretionary wedge
African geology
Andes Mountains
Antarctica
Arabian geology
Archean
Asian geology
asthenosphere
atmosphere
Australian geology
basin, sedimentary basin
beaches and shorelines
benthic, benthos
biosphere
Cambrian
Carboniferous
cave system, cave
Cenozoic
climate change
continental crust
continental drift
continental margin
convection and the Earth's mantle
convergent plate margin processes
coral
craton
Cretaceous
crust
crystal, crystal dislocations
deformation of rocks
deltas
deserts
Devonian
divergent plate margin processes
drainage basin (drainage system)
Earth
earthquakes
economic geology
Eocene
eolian
erosion
estuary
European geology
evolution
flood
fluvial
flysch
fossil
fracture
geoid
geomorphology
glacier, glacial systems
Gondwana, Gondwanaland
granite, granite batholith
greenstone belts
Grenville province and Rodinia
historical geology
hot spot
hydrocarbons and fossil fuels
hydrosphere
igneous rocks
impact crater structures
Indian geology
island arcs, historical eruptions
Japan
karst
large igneous provinces, flood basalt
lava
life's origins and early evolution
lithosphere
Madagascar
magma
mantle
mantle plumes
mass extinctions
mass wasting
mélange
Mesozoic
metamorphism and metamorphic rocks
meteor, meteorite
Milankovitch cycles
mineral, mineralogy
Neogene
Neolithic
North American geology
ocean basin
ocean currents
oceanic plateau
ophiolites
Ordovician
origin and evolution of the Earth and solar system
orogeny
ozone hole
paleoclimatology
Paleolithic
paleomagnetism
paleontology
Paleozoic
Pangaea
passive margin
pelagic, nektonic, planktonic
Permian
petroleum geology
petrology and petrography

Phanerozoic
photosynthesis
plate tectonics
Pleistocene
Precambrian
Proterozoic
Quaternary
radiation
radioactive decay
river system
Russian geology
seawater
sedimentary rock, sedimentation
seismology
sequence stratigraphy
Silurian
soils
South American geology
stratigraphy, stratification, cyclothem
structural geology
subduction, subduction zone
subsidence
Sun
supercontinent cycles
Tertiary
thermohaline circulation
transform plate margin processes
tsunami, generation mechanisms
unconformities
volcano
weathering
Wegener, Alfred

Earth and Space Science (Content Standard D): Origin and Evolution of the Universe

asteroid
astronomy
astrophysics
binary star systems
black holes
comet
cosmic microwave background radiation
cosmic rays
cosmology
dark matter
dwarfs (stars)
Einstein, Albert
galaxies
galaxy clusters
gravity wave
ice ages
interstellar medium
Jupiter
Mars
Mercury
meteor, meteorite
Neptune
nova
origin and evolution of the universe
planetary nebula
Pluto
pulsar
quasar
radiation
radio galaxies
Saturn
sea-level rise
solar system
star formation
stellar evolution
Sun
universe
Uranus
Venus

Science and Technology (Content Standard E)

astrophysics
cosmic microwave background radiation
electromagnetic spectrum
Galilei, Galileo
geochemistry
geochronology
geodesy
geodynamics
geographic information systems
geomagnetism, geomagnetic reversal
geophysics
gravity wave
gravity, gravity anomaly
Hubble, Edwin
magnetic field, magnetosphere
oceanography
paleomagnetism
radiation
remote sensing
seismology
telescopes
thermodynamics

Science in Personal and Social Perspectives (Content Standard F)

astronomy
aurora, aurora borealis, aurora australis
climate change
constellation
cosmology
Darwin, Charles
ecosystem
Einstein, Albert
El Niño and the Southern Oscillation (ENSO)
environmental geology
evolution
flood
Gaia hypothesis
geological hazards
global warming
greenhouse effect
hydrocarbons and fossil fuels
hydrosphere
island arcs, historical eruptions
life's origins and early evolution
mass extinctions
origin and evolution of the universe
sea-level rise
soils
subsidence
sun halos, sundogs, and sun pillars
supernova
tsunami, historical accounts

History and Nature of Science (Content Standard G)

astronomy
Bowen, Norman Levi
Brahe, Tycho
Cloud, Preston
Copernicus, Nicolas
Coriolis, Gustave
Dana, James Dwight
Darwin, Charles
Dewey, John F.
Du Toit, Alexander
Einstein, Albert
Eskola, Pentti
Galilei, Galileo
Gamow, George
Gilbert, Grove K.
Goldschmidt, Victor M.
Grabau, Amadeus William
Halley, Edmond
Hess, Harry
Hipparchus
Holmes, Arthur
Hubble, Edwin
Hutton, James
Huygens, Christian
Kepler, Johannes

Lawson, Andrew Cooper
Lemaître, Georges
Lyell, Sir Charles
Milankovitch, Milutin M.
Pettijohn, Francis John
Powell, John Wesley
Ptolemy, Claudius Ptolemaeus
Sedgwick, Adam
Smith, William H.
Sorby, Henry Clifton
Steno, Nicolaus
Stille, Wilhelm Hans
Wegener, Alfred
Werner, A. G.

Subdisciplines

astronomy
astrophysics
atmosphere
climate
cosmology
economic geology
evolution
geochemistry
geochronology
geodesy
geodynamics
geological hazards
geomorphology
geophysics
groundwater
historical geology
metamorphism and metamorphic rocks
meteorology
mineral, mineralogy
oceanography
paleoclimatology
paleomagnetism
paleontology
petroleum geology
petrology and petrography
plate tectonics
sedimentary rock, sedimentation
seismology
sequence stratigraphy
stratigraphy, stratification, cyclothem
structural geology
thermodynamics

ENTRIES A–Z

A

accretionary wedge Plate tectonic theory recognizes that the surface of the Earth is broken up into a few dozen rigid plates that are all moving relative to one another by sliding along a partially molten zone deep within the mantle. These plates can have one of three types of boundaries with each other, including divergent, convergent, and transform. Divergent margins form where the plates are moving apart, convergent margins form where the plates are moving toward each other, and transform (or strike-slip) margins form where the plates are sliding past each other. Along convergent plate margins, one tectonic plate is typically pushed or subducted beneath another plate along deep oceanic trenches. In most cases a dense oceanic plate is subducted beneath a less dense, overriding continental plate, and a chain of volcanoes known as a volcanic arc forms on the overriding plate. Accretionary wedges are structurally complex parts of these subduction zone systems that form on the landward side of the trench from material scraped off from the subducting plate, as well as trench fill sediments. They typically have wedge-shaped cross sections and one of the most complex internal structures of any tectonic element known on Earth. Parts of accretionary wedges are characterized by numerous thin units of rock layers that are repeated by numerous faults, known as thrust faults, along which the same unit may be stacked upon itself many times. Other parts or other wedges are characterized by a relatively large section of rocks with relatively few faults, and still other sections are dominated by folded units, packages of rocks. They also host rocks known as tectonic mélanges that are complex mixtures of blocks and thin slivers of rocks surrounded by thrust faults. The rock types in these mélanges are quite diverse and typically include greywacke, basalt, chert, and limestone, characteristically encased in a matrix of a different rock type (such as shale or serpentinite). Some accretionary wedges contain small blocks or layers of high-pressure, low-temperature metamorphic rocks (known as blueschists) that have formed deep within the wedge where pressures are high and temperatures are low because of the insulating effect of the cold subducting plate. These high-pressure rocks were brought to the surface by structural processes.

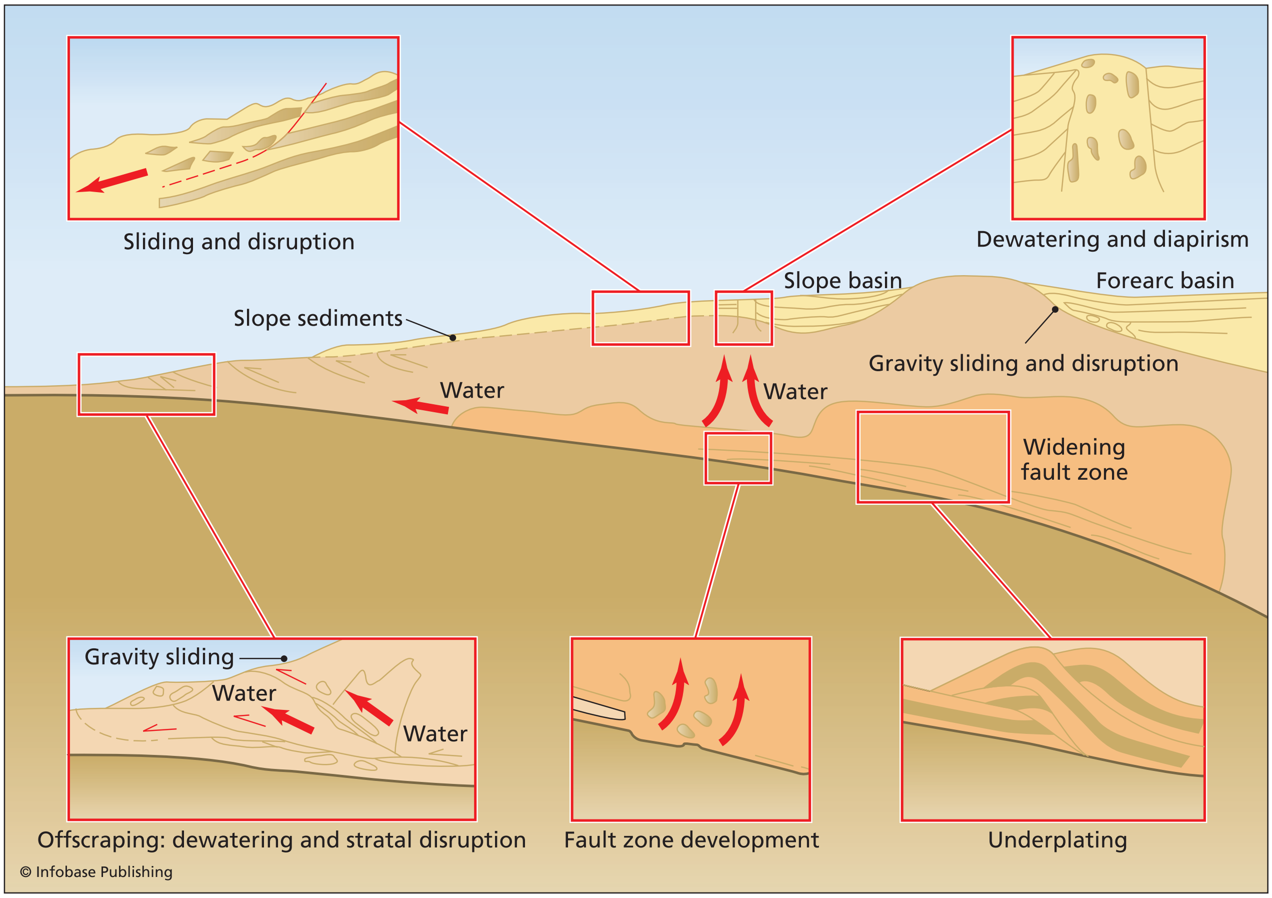
Accretionary wedges grow by the gradual process of scraping sedimentary and volcanic rock material from the trench and subducting plate, which constantly pushes new material in front of and under the wedge as plate tectonics drives plate convergence. The type and style of material offscraped and incorporated into the wedge depends on the type of material near the surface on the subducting plate. Subducting plates with thin layers of deep-sea sediment such as chert on their basaltic surface yield packages in the accretionary wedge dominated by basalt and chert rock types, whereas subducting plates with thick sequences of greywacke sediments yield packages (thrust slices of rock from the subducting plate) in the accretionary wedge dominated by greywacke. Prisms of accreted rock at convergent plate boundaries may also grow by a process known as underplating, where packages are added to the base of the accretionary wedge, a process that typically causes folding of the overlying parts of the wedge. The fronts or toes of accretionary wedges are also characterized by material slumping off of the steep slope of the wedge into the trench. This material can then be recycled back into the accretionary wedge to form even more complex structures. The processes of offscraping and underplating work together and rotate rock layers and structures to steeper orientations. In this way rock layers rotate from an orientation that is near horizontal at the toe of the wedge, to near vertical at the back of the wedge.

Accretionary wedges are thought to behave mechanically somewhat as if they were piles of sand or snow bulldozed in front of a plow. They grow into a triangular wedge shape in cross section that increases its slope until it becomes oversteepened and mechanically unstable, which then causes the toe of the wedge to advance by thrusting, or the top of the wedge to collapse by normal faulting. Either of these two processes can reduce the slope of the wedge and lead it to become more stable. In addition to the evidence for thrust faulting in accretionary wedges, structural geologists have documented many examples of normal faults where the tops of the wedges have collapsed, supporting models of extensional collapse of oversteepened wedges.

Accretionary wedges are forming above nearly every subduction zone on the planet. However, these accretionary wedges presently border open oceans that have not yet closed by plate tectonic processes. Eventually the movements of the plates and continents will cause the accretionary wedges to become involved in plate collisions that will dramatically change the character of the accretionary wedges. They are typically overprinted by additional shortening, faulting, folding, and high-temperature metamorphism, and intruded by magmas related to arcs and collisions. These later events, coupled with the initial complexity and variety, make identification of accretionary wedges in ancient mountain belts difficult, and prone to uncertainty.

DESCRIPTION OF A TYPICAL ACCRETIONARY WEDGE: SOUTHERN ALASKA'S CHUGACH TERRANE

Southern Alaska is underlain by a complex assemblage of accreted terranes, including the Wrangellia superterrane (consisting of three separate terranes called the Peninsular, Wrangellia, and Alexander terranes), and farther outboard, the Chugach–Prince William superterrane. During much of the Meso-



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Cross section of typical accretionary wedge, showing material being offscraped at the toe of the wedge and underplated beneath the wedge. Water escapes upward through the accretionary wedge, causing the wedge material to become denser and more compacted.

zoic, the two superterranes formed a magmatic arc and accretionary wedge, respectively, above a circum-Pacific subduction zone. The Border Ranges fault forms the boundary between the Wrangellia and Chugach–Prince William superterranes; it initiated as a subduction thrust but has been reactivated in various places as a strike-slip or normal fault. On the Kenai Peninsula the Chugach terrane contains two major units. The unit located farther inland, the McHugh complex, is composed mainly of basalt, chert, argillite, and greywacke, as well as several large ultramafic massifs. Pinhead-sized marine fossils called radiolarians from McHugh cherts throughout south-central Alaska range in age from middle Triassic to middle Cretaceous. The interval during which the McHugh complex formed by subduction and accretion is not well known but probably spanned most of the Jurassic and Cretaceous. The McHugh has been thrust seaward on the Eagle River/Chugach Bay fault over a relatively coherent tract of trench turbidites assigned to the Upper Cretaceous Valdez Group. After the protracted episode of subduction-accretion that built the Chugach terrane, the accretionary wedge was cut by near-trench intrusive rocks, assigned to the Sanak-Baranof plutonic belt, probably related to ridge subduction.

The McHugh complex of south-central Alaska and its lateral equivalent, the Uyak complex of Kodiak, are part of the Mesozoic/Cenozoic accretionary wedge of the Chugach terrane. The vast extent of the McHugh complex has proven to be of value in reconstructing the tectonics of the Pacific realm and has been compared with similar tracts such as the Franciscan complex of California and the Shimanto Belt of Japan. The evolution of the McHugh and its equivalents can be broken down into three broad, somewhat overlapping phases: (1) origin of igneous and sedimentary rocks; (2) incorporation into the subduction complex (“accretion”), and attendant deformation and metamorphism; and (3) younger deformations.

Few fossil ages have been reported from the McHugh complex, but at several places on the Kenai Peninsula radiolarian chert depositionally overlies pillow basalt. Precise radiolarian age calls show that the base of the chert varies in age from middle Triassic to middle Cretaceous. Greywacke depositionally overlying chert has yielded Early Jurassic radiolarians. These ages are readily explained by a stratigraphic model in which the McHugh basalts were formed by seafloor spreading, the overlying cherts were deposited on the ocean floor as it was conveyed toward a trench, and the argillite and greywacke record deposition in the trench, just prior to subduction-accretion. The timing of subduction-accretion is not well known but probably spanned most of the Jurassic and Cretaceous.

Limestones within the McHugh complex are of two categories. A limestone clast in McHugh conglomerate has yielded conodonts with a possible age range of Late Mississippian to Early Pennsylvanian. This clast could have been shed from the Wrangellia terrane. Most of the dated limestones, however, are tectonic blocks typically occurring as severely extended strings of boudins that have yielded Permian fusulinids or conodonts. Both the fusulinids and conodonts are of shallow-water, tropical, Tethyan affinity; the fusulinids are quite distinct from those of Wrangellia. The limestone blocks might represent the tops of seamounts that were decapitated at the subduction zone. If so, some of the ocean floor offscraped to form the McHugh complex must have formed in the Paleozoic.

The seaward part of the Chugach terrane is underlain by the Valdez group of Late Cretaceous age. On the Kenai Peninsula it includes medium- and thin-bedded greywacke turbidites, black argillite, and minor pebble to cobble conglomerate. These strata were probably deposited in a deep-sea trench and accreted shortly thereafter. Most of the Valdez group consists of relatively coherent strata, deformed into regional-scale tight- to isoclinal folds, cut by a slaty cleavage. The McHugh complex and Valdez group are juxtaposed along a thrust, which in the area of Turnagain Arm has been called the Eagle River fault, and on the Kenai Peninsula is known as the Chugach Bay thrust. Beneath this thrust is a mélange of partially to thoroughly disrupted Valdez group turbidites. This monomict mélange, which is quite distinct from the polymict mélanges of the McHugh complex, can be traced for many kilometers in the footwall of the Eagle River thrust and its along-strike equivalents.

In early Tertiary time, the Chugach accretionary wedge was cut by near-trench intrusive rocks forming the Sanak-Baranof plutonic belt. The near-trench magmatic pulse migrated 1,370 miles (2,200 km) along the continental margin, from about 63–65 million years ago at Sanak Island in the west, to about 50 million years ago at Baranof Island in the east. The Paleogene near-trench magmatism was related to subduction of the Kula-Farallon spreading center.

Mesozoic and Cenozoic rocks of the accretionary wedge of south-central Alaska are cut by abundant late brittle faults. Along Turnagain Arm near Anchorage, four sets of late faults are present: a conjugate pair of east-northeast-striking dextral and northwest-striking sinistral strike-slip faults, north-northeast-striking thrusts, and less abundant west-northwest-striking normal faults. All four fault sets are characterized by quartz ± calcite ± chlorite fibrous slickenside surfaces and appear to be approximately coeval. The thrust- and strike-slip faults together resulted in subhorizontal shortening perpendicular to strike, consistent with an accretionary wedge setting. Motion on the normal faults resulted in extension of the wedge but is of uncertain tectonic significance. Some of the late brittle faults host gold-quartz veins that are the same age as nearby near-trench intrusive rocks. By implication, the brittle faulting and gold mineralization are probably related to ridge subduction.

Scattered fault-bounded ultramafic-mafic complexes in southern Alaska stretch 600 miles (1,000 km) from Kodiak Island in the south to the Chugach Mountains in the north. These generally consist of dunite +/- chromite, several varieties of peridotite, which grade upward into gabbronorites. These rocks are intruded by quartz diorite, tonalite, and granodiorite. Because of general field and mineralogic similarities, these bodies are generally regarded as having a similar origin and are named the Border Ranges ultramafic-mafic complex (BRUMC). The BRUMC includes six bodies on Kodiak and Afognak Islands, plus several on the Kenai Peninsula (including Red Mountain) and other smaller bodies. In the northern Chugach Mountains the BRUMC includes the Eklutna, Wolverine, Nelchina, and Tonsina complexes, and the Klanelneechena complex in the central Chugach Mountains.

Some models for the BRUMC suggest that all these bodies represent cumulates formed at the base of an intraoceanic arc sequence, and were formed at the same time as volcanic rocks now preserved on the southern edge of the Wrangellian composite terrane located in the Talkeetna Mountains. Some of the ultramafic massifs on the southern Kenai Peninsula, however, are not related to this arc, but represent deep oceanic material accreted in the trench. The ultramafic massifs on the Kenai Peninsula appear to be part of a dismembered assemblage that includes the ultramafic cumulates at the base, gabbroic-basalt rocks in the center, and basalt-chert packages in the upper structural slices. The ultramafic massifs may represent pieces of an oceanic plate subducted beneath the Chugach terrane, with fragments offscraped and accreted during the subduction process. There are several possibilities as to what the oceanic plate may have been, including normal oceanic lithosphere, an oceanic plateau, or an immature arc. Alternatively, the ultramafic/mafic massifs may represent a forearc or suprasubduction zone ophiolite, formed seaward of the incipient Talkeetna (Wrangellia) arc during a period of forearc extension.

See also ASIAN GEOLOGY; CONVERGENT PLATE MARGIN PROCESSES; DEFORMATION OF ROCKS; MÉLANGE; PLATE TECTONICS; STRUCTURAL GEOLOGY.

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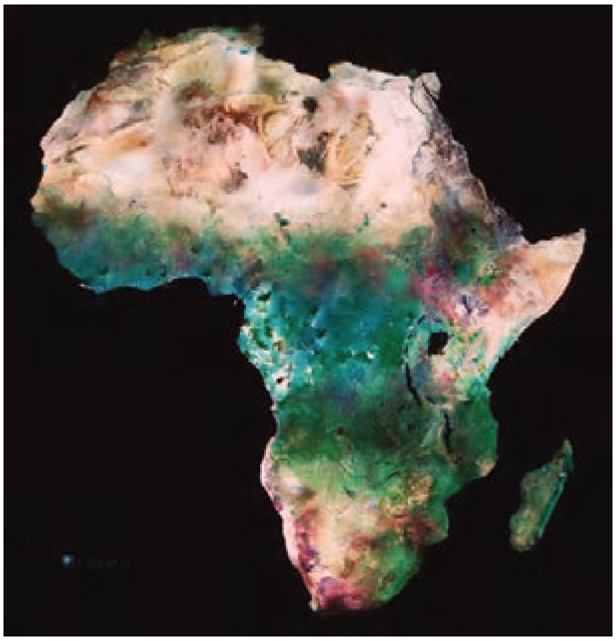
African geology

The continent of Africa consists of several old nuclei of very old (Archean) rocks called cratons that were welded together along younger (Proterozoic) mountain belts called orogenic belts that formed during collision of the cratons in the Late Precambrian. The cratons include the intensely studied Kalahari craton, comprising two Archean cratons known as the Kaapvaal and Zimbabwe cratons, plus the less well-known Congo and West African cratons. The Madagascar craton, which used to be attached to the African continent, lies off the coast of East Africa. These cratons are sutured along orogenic belts colloquially known as *Pan African orogens,* a term that is sometimes used to refer to the belts of rocks affected by complex igneous, metamorphic, and structural events that cut across Africa and many other continental masses between about 1,000 and 500 million years ago. The northern and southern margins of the African continent are affected by Paleozoic-Mesozoic deformation and mountain building, and the eastern side of the continent is experiencing active rifting and breakup into microplates, one of which extends through Madagascar and links with the Indian-Australian ridge.

KALAHARI CRATON

Southern Africa's Kalahari craton is composed of two older cratons, the Kaapvaal and Zimbabwe, that collided and were sutured 2.5 billion years ago along the Limpopo belt and have acted as a single craton since that time. For times before 2.5 billion years ago, therefore, the two parts (Kaapvaal and Zimbabwe cratons) are discussed separately, but from the Proterozoic onward, most geologists refer to the amalgamated cratons as the Kalahari craton.



True-color composite satellite image of Africa from data collected by the Thematic Mapper instrument on an American Landsat satellite. The Sahara is the brown (dry) area across the northern part of the continent, the Congo basin is lush green in the center, and the steppes of southern Africa are in the south. Madagascar lies off the southeastern coast. *(Earth Satellite Corporation/Photo Researchers Inc.)*

Kaapvaal Craton, South Africa

The Archean Kaapvaal craton of southern Africa contains some of the world's oldest and most intensely studied Archean rocks, yet nearly 86 percent of the craton is covered by younger rocks. The craton covers approximately 363,000 square miles (585,000 km^2) near the southern tip of the African continent. The craton is bordered on the north by the high-grade Limpopo mobile belt, initially formed when the Kaapvaal and Zimbabwe cratons collided at 2.6 billion years ago. On its southern and western margins the craton is bordered by the Namaqua-Natal Proterozoic orogens, and it is overlapped on the east by the Lebombo sequence of Jurassic rocks recording the breakup of Gondwana.

Most of the rocks composing the Archean basement of the Kaapvaal craton are granitoids and gneisses, along with less than 10 percent greenstone belts known locally as the Swaziland Supergroup. The oldest rocks are found in the Ancient Gneiss complex of Swaziland, where a 3.65–3.5 billion-year-old bimodal gneiss suite consisting of interlayered tonalite-trondhjemite-granite and amphibolite

Map of Africa showing cratons, orogens, rifts, and main geographic elements. The Kalaharai craton in the south comprises the Zimbabwe and Kaapvaal cratons, the Congo craton occupies much of central Africa, and the West African craton is located in northwest Africa. The East African Orogen includes the Arabian-Nubian shield in the north and the Mozambique Belt in the south, whereas the active East African Rift cuts from the Gulf of Aden past Lake Victoria to the Mozambique Channel, and offshore to Madagascar. The Atlas Mountains are located in northwest Africa. *(modeled from Alan Goodwin, 1991)*

are complexly folded together with migmatitic gneiss, biotite-hornblende tonalitic gneiss, and lenses of 3.3–3.0 billion-year-old quartz monzonite. Several folding and deformation events are recognized from the Ancient Gneiss complex, whose history spans a longer interval of 700 million years, longer than the entire Phanerozoic.

There are six main greenstone belts in the Kaapvaal craton, the most famous of which is the Barberton greenstone belt. Although many studies have attempted to group all of the greenstone sequences of the Kaapvaal craton into the term *Swaziland Supergroup,* there is little solid geochronologic or other evidence that any of these complexly deformed belts are contemporaneous or related to each other, so this usage is not recommended. Other greenstone belts include the Murchison, Sutherland, Amalia, Muldersdrif, and Pietersburg belts. U-Pb (Uranium-Lead) isotopic ages from these belts span the interval from 3.5 to 3.0 billion years ago, a period of 500 million years. The greenstone belts include structurally repeated and complexly folded and metamorphosed sequences of tholeiitic basalts, komatiites, picrites, cherts (or metamorphosed felsic mylonite), felsic lava, clastic sediments, pelites, and carbonates. Possible partial ophiolite sequences have been recognized in some of these greenstone belts, particularly in the Jamestown section of the Barberton belt.

One of the long-held myths about the structure of greenstone belts in the Kaapvaal craton is that they represent steep synclinal keels of supracrustal rocks squeezed between diapiric granitoids. Detailed structural studies of the Murchison greenstone belt have established, however, that there is a complete lack of continuity of strata from either side of the supposed syncline of the Murchison belt, and that the structure is much more complex than the pinched-synform model predicts. Downward-facing structures and fault-bounded panels of rocks with opposing directions of younging (the direction toward the younger beds) and indicators of isoclinal folding have been documented, emphasizing that the "stratigraphy" of this and other belts cannot be reconstructed until the geometry of deformation is better understood; early assumptions of a simple synclinal succession are invalid.

Detailed mapping in a number of greenstone belts in the Kaapvaal craton has revealed early thrust faults and associated recumbent nappe-style folds. Most do not have any associated regional metamorphic fabric or axial planar cleavage, making their identification difficult without very detailed structural mapping. In some cases late intrusive rocks have utilized the zone of structural weakness provided by the early thrusts for their intrusion.

A complex series of tectonic events is responsible for the present structural geometry of the greenstone belts of the Kaapvaal craton. Early regional recumbent folds, thrust faults, inverted stratigraphy, juxtaposition of deep and shallow water facies, nappes, and precursory olistostromes related to the northward tectonic emplacement of the circa 3.5 Ga Barberton greenstone collage on gneissic basement have been documented. The thrusts may have been zones of high fluid pressure resulting from hydrothermal circulation systems surrounding igneous intrusions, and are locally intruded by syn-tectonic 3.43–3.44 billion-year-old felsic igneous rocks. Confirmation of thrust-style age relationships comes from recent U-Pb zircon work, which has shown that older (circa 3.482 ± 5 Ga) Komatii Formation rocks lie on top of younger (circa 3.453 ± 6 Ga) Theespruit Formation.

The Pietersburg greenstone belt is located north of the Barberton and Murchison belts, near the high-grade Limpopo belt. Greenschist to amphibolite facies oceanic-affinity basaltic pillow lavas, gabbros, peridotites, tuffs, metasedimentary rocks, and banded iron formation are overlain unconformably by a terrestrial clastic sequence deposited during a second deformation event marked by northward-directed thrusting between 2.98 and 2.69 billion years ago. Coarse clastic rocks deposited in intermontaine basins are imbricated with the oceanic affinity rocks and were carried piggyback on the moving allochthon. Syn-thrusting depositional troughs became tightened into synclinal structures during the evolution of the thrust belt, and within the coarse-clastic section it is possible to find thrusts that cut local unconformities, and unconformities that cut thrusts.

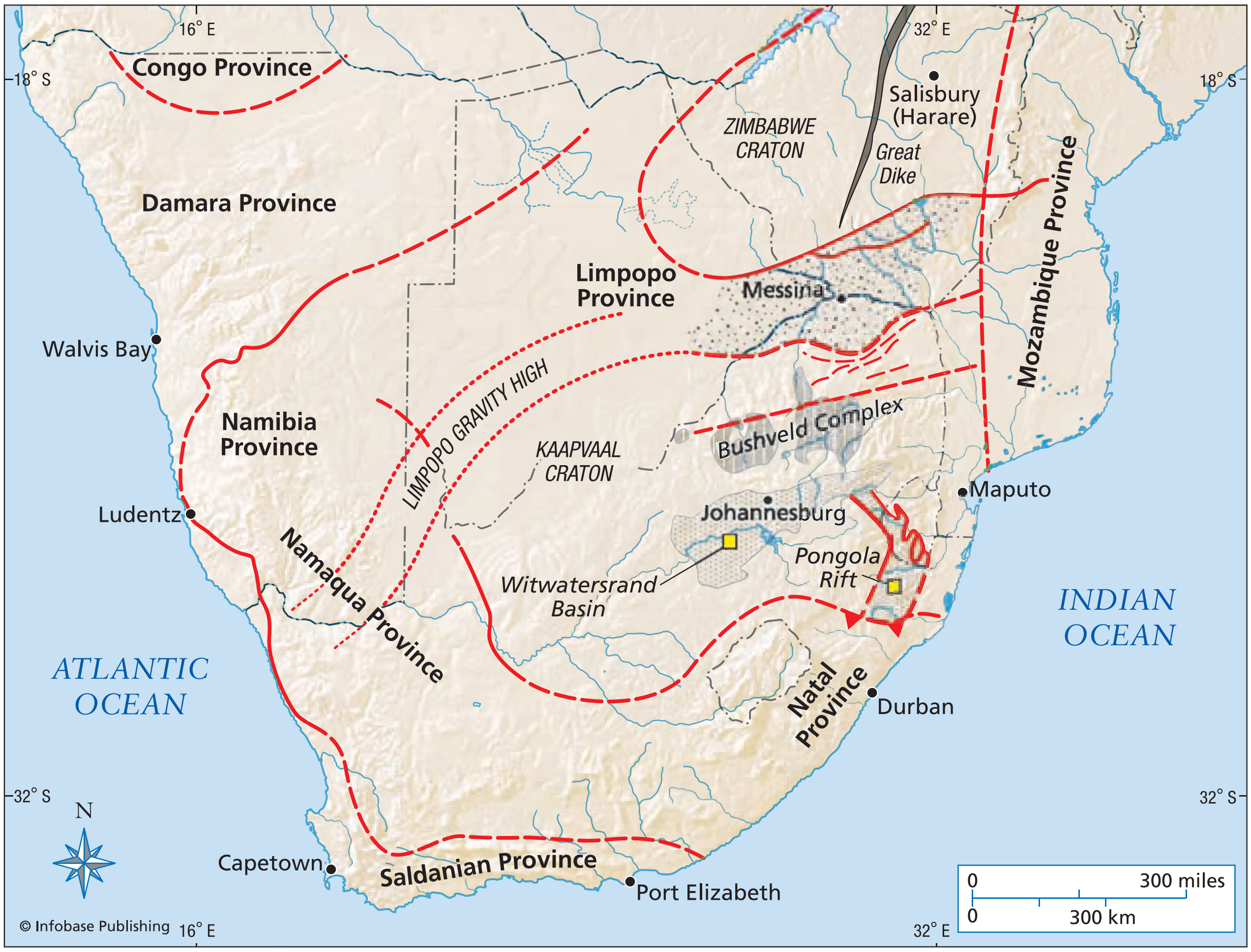
The granite-greenstone terrane is overlain unconformably by the 3.1 billion-year-old Pongola Supergroup that has been proposed to be the oldest well-preserved continental rift sequence in the world. Deposition of these shallow-water tidally influenced sediments was followed by a widespread granite intrusion episode at 3.0 billion years ago. The next major events recorded include the formation of the West Rand Group of the Witwatersrand basin on the cratonward side of an Andean arc around 2.8 billion years ago, then further deposition of the extremely auriferous sands of the Central Rand Group in a collisional foreland basin formed when the Zimbabwe and Kaapvaal cratons collided. This collision led to the formation of a continental extensional rift province in which the Ventersdorp Supergroup was deposited at 2.64 billion years ago, with the extension occurring at a high angle to the collision. The latest Archean through Early Proterozoic history of the Kaapvaal craton is marked by deposition of the 2.6–2.1 billion-year-old Transvaal Supergroup in a shallow sea, perhaps related to slow thermal subsidence following Ventersdorp rifting. The center of the Witwatersrand basin is marked by a large circular structure called the Vredefort dome. This structure, several tens of kilometers wide, is associated with shock metamorphic structures, melts, and extremely high-pressure phases of silica, suggesting that it represents a meteorite impact structure.

The Bushveld complex is the world's largest layered mafic-ultramafic intrusion, located near the northern margin of the Kaapvaal craton. The complex occupies an area of 40,000 square miles (65,000 km^2) and intrudes Late Archean-Early Proterozoic rocks of the Transvaal Supergroup. Isotopic studies using a variety of methods have yielded age estimates of 2.0–2.1 billion years, with some nearby intrusions yielding ages as young as 1.6 billion years. The complex consists of several lobes with a conelike form, and contains numerous repeating cycles of mafic, ultramafic, and lesser felsic rocks. Several types of ores are mined from the complex, including chromite, platinum-group metals, cobalt, nickel, copper, and vanadiferous iron ores. Nearly 70 percent of the world's chrome reserves are located in the Bushveld complex. The mafic phases of the complex include dunite, pyroxenite, harzburgite, norite, anorthosite, gabbro, and diorite. The center of the complex includes felsic rocks, including granophyres and granite.

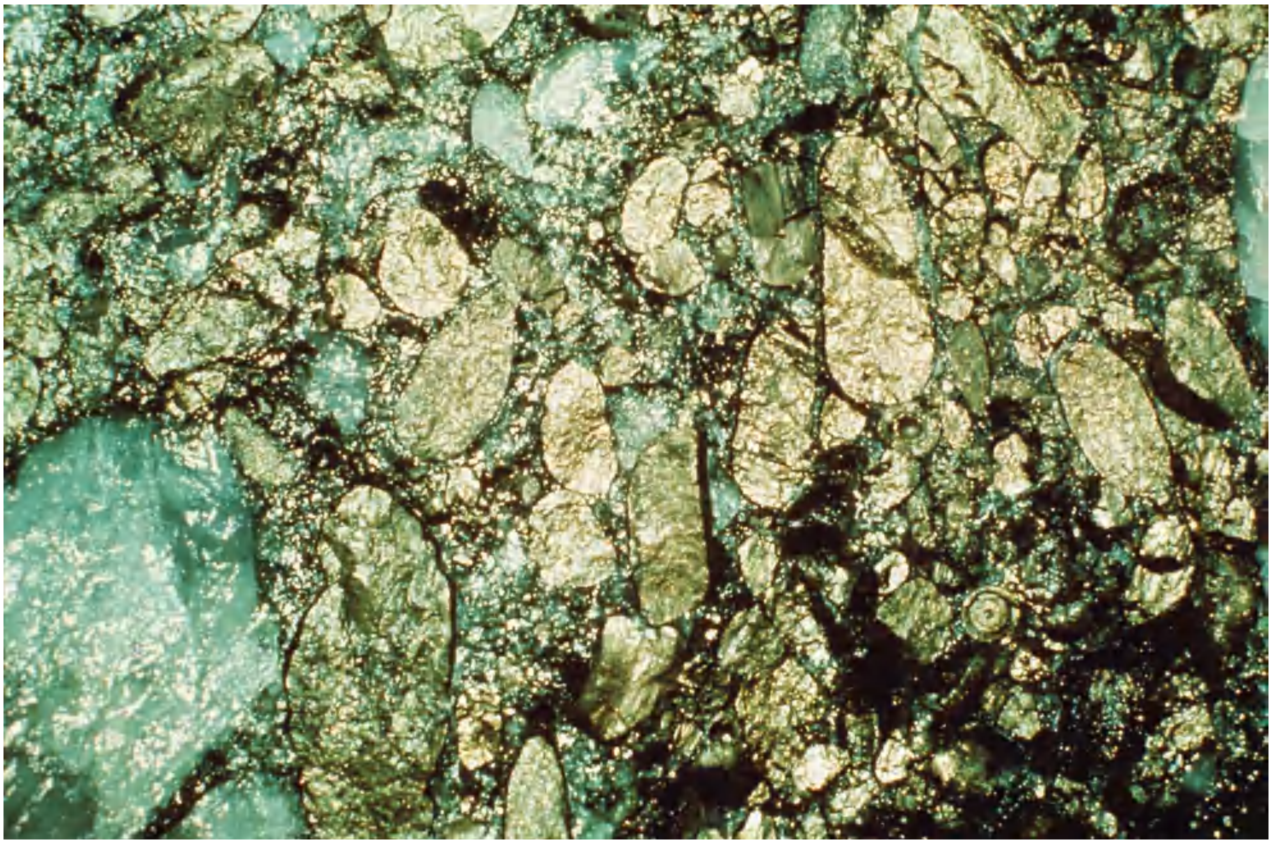
Much of the Kaapvaal craton is covered by rocks of the Karoo basin, including fluvial-deltaic deposits and carbonaceous deposits including coal. The top of the Karoo Sequence includes mafic and felsic lavas that were erupted soon before the breakup of Gondwana 200 million years ago.

Witwatersrand Basin

The Witwatersrand basin on South Africa's Kaapvaal craton is one of the best known of Archean sedimentary basins, and it contains some of the largest gold reserves in the world, accounting for more than 55 percent of all the gold ever mined. Sediments in the basin include a lower flysch-type sequence, and an upper molassic facies, both containing abundant silicic volcanic detritus. The strata are thicker and more proximal on the northwestern side of the basin that is at least locally fault-bounded. The Witwatersrand basin is a composite foreland basin that developed initially on the cratonward side of an Andean arc, similar to retroarc basins forming presently behind the Andes. A continental collision between the Kaapvaal and Zimbabwe cratons 2.7



Map of the Kaapvaal and Zimbabwe cratons, showing the Great Dike on the Zimbabwe craton, the Witwatersrand and Pongola basins on the Kaapvaal craton, the Bushveld complex, and Limpopo Province separating the two cratons. Other major tectonic elements of southern Africa are also shown.



Mineralized conglomerate forming gold ore from the Archean Witwatersrand basin on the Kaapvaal craton *(Brooks Kraft/Corbis)*

billion years ago caused further subsidence and deposition in the Witwatersrand basin. Regional uplift during this later phase of development placed the basin on the cratonward edge of a collision-related plateau, now represented by Limpopo Province. There are many similarities between this phase of development of the Witwatersrand basin and basins such as the Tarim and Tsaidam, north of the Tibetan Plateau.

The Witwatersrand basin is an elongate trough filled predominantly by 2.8–2.6 billion-year-old clastic sedimentary rocks of the West Rand and Central Rand Groups, together constituting the Witwatersrand Supergroup. These are locally, in the northwestern parts of the basin, underlain by the volcano sedimentary Dominion Group. The structure strikes in a northeasterly direction parallel with, but some distance south of, the high-grade gneissic terrane of Limpopo Province. The high-grade metamorphism, calc-alkaline plutonism, uplift, and cooling in the Limpopo are of the same age as and closely related to the evolution of the Witwatersrand basin. Strata dip inward with dips greater on the northwestern margin of the basin than on the southeastern margin. The northwestern margin of the basin is a steep fault that locally brings gneissic basement rocks into contact with Witwatersrand strata to the south. Dips are vertical to overturned at depth near the fault, but only 20° near the surface, demonstrating that this is a thrust fault. A number of folds and thrust faults are oriented parallel to the northwestern margin of the basin.

The predominantly clastic sedimentary fill of the Witwatersrand basin has been divided into the West Rand and the overlying Central Rand Groups, which rest conformably on the largely volcanic Dominion Group. The Dominion Group was deposited over approximately 9,000 square miles (15,000 km^2), but it is correlated with many similar volcanic groups along the northern margin of the Kaapvaal craton. The Dominion Group and its correlatives, and a group of related plutons, have been interpreted as the products of Andean arc magmatism, formed above a 2.8 billion-year-old subduction zone that dipped beneath the Kaapvaal craton. The overlying West Rand and Central Rand Groups were deposited in a basin at least 50,000 square miles (80,000 km^2). Stratigraphic thicknesses of the West Rand Group generally increase toward the fault-bounded northwestern margin of the basin, whereas thicknesses of the Central Rand Group increase toward the center of the basin. Strata of both groups thin considerably toward the southeastern basin margin. The northeastern and southwestern margins are poorly defined, but some correlations with other strata (such as the Godwan Formation) indicate that the basin was originally larger than the present basin. Strata originally deposited north of Johannesburg are buried, removed by later uplift, omitted by igneous intrusion, and cut out by faulting.

The West Rand Group consists of southeastward tapering sedimentary wedges that overlie the Dominion Group, and were deposited directly on top of granitic basement in many places. The maximum thickness of the West Rand Group, 25,000 feet (7,500 m), occurs along the northern margin of the basin, and the group thins southeast to a preserved thickness of 2,700 feet (830 m) near the southern margin. Shale and sandstone in approximately equal proportions characterize the West Rand Group, and a thin horizon of mafic volcanics is locally present. This volcanic horizon thickens to 800 feet (250 m) near the northern margin of the basin, but is absent in the south. The West Rand Group contains mature quartzites, minor chert, and sedimentation patterns indicating both tidal and aeolian reworking. Much of the West Rand Group is an ebb-dominated tidal deposit later influenced by beach-swash deposition. More shales are preserved near the top of the group. Overall, the West Rand Group preserves a transition from tidal flat to beach, then deeper water deposition indicates a deepening of the Witwatersrand basin during deposition. Upper formations in the West Rand Group contain magnetic shales and other fine-grained sediments suggestive of a distal shelf or epicontinental sea environment of deposition.

The lower West Rand Group records subsidence of the Witwatersrand basin since the sediments grade vertically from beach deposits to a distal shallow marine facies. This transition means that the water was becoming deeper during deposition, showing that there was active subsidence of the basin. Since there is a lack of coarse, immature, angular conglomerate and breccia-type sediments, the subsidence was probably accommodated by gentle warping and flexure, not by faulting. A decreasing rate of subsidence and/or a higher rate of clastic sediment supply is indicated by the progressively shallower-water facies deposits in the upper West Rand Group. Numerous silicic volcanic clasts in the West Rand Group indicate that a volcanic arc terrane to the north was contributing volcanic detritus to the Witwatersrand basin. Additionally, the presence of detrital ilmenite, fuchsite, and chromite indicate that an ultramafic source such as an elevated greenstone belt was also contributing detritus to the basin.

The Central Rand Group was deposited conformably on top of the West Rand Group and attains a maximum preserved thickness of 9,500 feet (2,880 m) northwest of the center of the basin, and north of the younger Vredefort impact structure. Sediments of the Central Rand Group consist of coarse-grained graywackes and conglomerates along with subordinate quartz sandstone interbedded with local lacustrine or shallow marine shales and siltstones. The conglomerates are typically poorly sorted and have large clasts with well-rounded shapes, while the smaller pebbles have angular to subangular shapes. Paleocurrent indicators show that the sediments prograded into the basin from the northwestern margin in the form of a fan-delta complex. This is economically important because numerous goldfields in the Central Rand Group are closely associated with major entry points into the basin. Some transport of sediments along the axis of the basin is indicated by paleocurrent directions in a few locations. A few volcanic ash (tuffaceous) horizons and a thin mafic lava unit are found in the Central Rand Group in the northeast part of the basin. The great dispersion of unimodal paleocurrent directions derived from most of the Central Rand Group indicates that these sediments were deposited in shallow-braided streams on coalescing alluvial fans. The paleorelief is estimated at 20 feet (6 m) in areas proximal to the source, and 1–2 feet (0.5 m) in more distal areas. Some of the placers in the Central Rand Group have planar upper surfaces, commonly associated with pebbles and heavy placer mineral concentrations, which may be attributed to reworking by tidal currents. Clasts in the conglomerates include vein quartz, quartz arenite, chert, jasper, silicic volcanics, shales and schists, and other rare rocks.

The Central Rand Group contains a large amount of molassic-type sediments disposed as sand and gravel bars in coalesced alluvial fans and fluvial systems. The West Rand/Central Rand division of the Witwatersrand basin into a lower flysch-type sequence and an upper molasse facies is typical of foreland basins. Extensive mining of paleoplacers for gold and uranium has enabled mapping of the dendritic paleodrainage patterns and the points of entry into the basin to be determined. The source of the Central Rand sediments was a mountain range located to the northwest of the basin, and this range contained a large amount of silicic volcanic material.

The growth of folds parallel to the basin margin during sedimentation and the preferential filling of synclines by some of the mafic lava flows in the basin indicate that folding was in progress during Central Rand Group sedimentation. Deformation of this kind is diagnostic of flexural foreland basins, and studies show that the depositional axis of the basin migrated southeastward during sedimentation, with many local unconformities related to tilting during flexural migration of the depositional centers.

The Witwatersrand basin exhibits many features characteristic of foreland basins, including an asymmetric profile with thicker strata and steeper dips toward the mountainous flank, a basal flysch sequence overlain by molassic-type sediments, and thrust faults bounding one side of the basin. Compressional deformation was in part syn-sedimentary and associated folds and faults strike parallel to the basin margins, and the depositional axis migrated away from the thrust front with time, as in younger foreland basins. Stratigraphic relationships within the underlying Dominion Group, the presence of silicic volcanic clasts throughout the stratigraphy, and minor lava flows within the basin suggest that the foreland basin was developed behind a volcanic arc, partly preserved as the Dominion Group. Sediments of the West Rand Group are interpreted as deposited in an actively subsiding foreland basin developed adjacent to an Andean margin and fold thrust belt.

Deformation in Limpopo Province and the northern margin of the Kaapvaal craton are related to a collision between the northern Andean margin of the Kaapvaal craton with a passive margin developed on the southern margin of the Zimbabwe craton that began before 2.64 billion years ago, when Ventersdorp rifting, related to the collision, commenced. It is possible that some of the rocks in the Witwatersrand basin, particularly the molasse of the Central Rand Group, may represent erosion of a collisional plateau developed as a consequence of this collision. The plateau would have been formed in the region between the Witwatersrand basin and Limpopo Province, a region characterized by a deeply eroded gneiss terrane. A major change in the depositional style occurs in the Witwatersrand basin between the Central Rand and West Rand Groups, and this break may represent the change from Andean arc retroarc foreland basin sedimentation to collisional plateau erosion–related phases of foreland basin evolution.

Paleoplacers in the Witwatersrand basin have yielded more than 850 million tons of gold, dwarfing all the world's other gold placer deposits put together. Many of the placer deposits (called *reefs* in local terminology) preserved detrital gold grains on erosion surfaces, along foreset beds in cross-laminated sandstone and conglomerate, in trough cross-beds, in gravel bars, and as detrital grains in sheet sands. Most of the gold is located close to the northern margin of the basin in the fluvial channel systems. Some of the gold flakes in more distal areas were trapped by stromatolite-like filamentous algae, and some appear to have even been precipitated by types of algae, although it is more likely that these are fine, recrystallized grains trapped by algal filaments. Besides gold more than 70 other ore minerals are recognized in the Witwatersrand basin; most are detrital grains, and others are from metamorphic fluids. The most abundant detrital grains include pyrite, uraninite, brannerite, arsenopyrite, cobaltite, chromite, and zircon. Gold-mining operations in the Witwatersrand employ more than 300,000 people and have led to the economic success of South Africa.

ZIMBABWE CRATON

The Zimbabwe craton is a classic granite greenstone terrane. In 1971 Clive W. Stowe, in a Ph.D. dissertation and publication from the University of London, proposed a division of the Zimbabwean (then Rhodesian) craton into four main tectonic units. His first unit includes remnants of older gneissic basement in the central part of the craton, including the Rhodesdale, Shangani, and Chilimanzi gneissic complexes. Stowe's second (northern) unit includes mafic and ultramafic volcanics overlain by a mafic/felsic volcanic sequence, iron formation, phyllites, and conglomerates of the Bulawayan Group all overlain by sandstones of the Shamvaian Group. The third, or southern, unit consists of mafic and ultramafic lavas of the Bulawayan Group, overlain by sediments of the Shamvaian Group. The southern unit is folded about east-northeast axes. Stowe defined a fourth unit in the east, including remnants of schist and gneissic rocks, enclosed in a sea of younger granitic rocks. Stowe was a leader in recognizing complex structures in greenstone belts, stating in his dissertation and 1974 paper that the Selukwe greenstone belt "appears to be part of an imbricated and overturned lower limb of a large recumbent fold, resting allochthonously on a gneissic basement." In 1979 John F. Wilson, a geologist from the Geological Survey of Rhodesia (now Zimbabwe), proposed a regional correlation between the greenstone belts in the craton. His general comparison of the compositions of the upper volcanics in the greenstone belts resulted in a distinction between the greenstone belts located in the western part of the craton from those in the eastern section. The greenstone belts to the west of his division are composed of dominantly calc-alkaline rock suites including basalt, andesite, and dacite flows and pyroclastic rocks. This western section includes bimodal volcanic rocks consisting of tholeiite and magnesium-rich pillow basalt and massive flows, with some peridotitic rocks alternating with dacite flows, tuffs, and agglomerates. The eastern section of the Zimbabwe craton is characterized by pillowed and massive tholeiitic basalt flows and less abundant magnesium-rich basalts and their metamorphic equivalents. The eastern section contains a number of phyllites, banded iron formations, local conglomerate, and grit and rare limestone. Wilson identified an area of well-preserved 3.5 billion-year-old gneissic rocks and greenstones in the southern part of the province, and named this the Tokwe segment. He suggested that this may be a "mini-craton," and that the rest of the Zimbabwe craton stabilized around this ancient nucleus.

Despite these early hints that the Zimbabwe craton may be composed of a number of distinct terranes, much of the work on rocks of the Zimbabwe craton has been geared toward making lithostratigraphic correlations between these different belts, and attempting to link them all to a single supergroup-style nomenclature. Many workers attempted to pin the presumably correlatable 2.7 billion-year-old stratigraphy of the entire Zimbabwe craton to an unconformable relationship between older gneissic rocks and overlying sedimentary rocks exposed in the Belingwe greenstone belt. More recently, Timothy Kusky, Axel Hoffman, and others have emphasized that the sedimentary sequence unconformably overlying the gneissic basement may be separated from the mafic/ultramafic magmatic sequences by a regional structural break, and that the presence of a structural break in the type of stratigraphic section for the Zimbabwe craton casts doubt on the significance of any lithostratigraphic correlations across Stowe's divisions of the craton.

Central Gneissic Unit (Tokwe Terrane)

Three and a half billion-year-old gneissic and greenstone rocks are well exposed in the area between Masvingo (Fort Victoria), Zvishavane (Shabani), and Shurugwi (Selukwe), in the Tokwe segment. The circa 3.5–3.6 billion-year-old Mashaba tonalite forms a relatively central part of this early gneissic terrane,

The Great Dike, a 2.5 billion-year-old magmatic intrusion in Zimbabwe, seen from the space shuttle *Endeavour* during mission STS-54, January 13–19, 1993 *(NASA/Photo Researchers, Inc.)*

and other rocks include mainly tonalitic to granodioritic, locally migmatitic gneissic units such as the circa 3.475 billion-year-old Tokwe River gneiss, Mushandike granitodiorite (2.95 billion years old), 3.0 billion-year-old Shabani gneiss, and 3.5 billion-year-old Mount d'Or tonalite. Similar rocks extend in both the northeast and southwest directions, but they are less well exposed and intruded by younger rocks in these directions. The Tokwe terrane probably extends to the northeast to include the area of circa 3.5 Ga greenstones and older gneissic rocks southeast of Harare. The Tokwe segment represents the oldest known portion of the Tokwe terrane, which was acting as a coherent terrane made up of 3.5–2.95 billion-year-old tectonic elements by circa 2.9 Ga.

The 3.500–2.950 billion-year-old Tokwe terrane also contains numerous narrow greenstone belt remnants, which are typically strongly deformed and multiply folded along with interlayered gneiss. The area in the northeasternmost part of the central gneissic terrane southeast of Harare best exhibits this style of deformation, although it continues southwest through Shurugwi. In the Mashava area west of Masvingo, ultramafic rocks, iron formations, quartzites, and mica schist are interpreted as 3.5 billion-year-old greenstone remnants tightly infolded with the ancient gneissic rocks. The 3.5 billion-year-old Shurugwi (Selukwe) greenstone belt was the focus of Clive W. Stowe's classic studies in the late 1960s, in which he identified Alpine-type inverted nappe structures and proposed that the greenstone belt was thrust over older gneissic basement rocks, forming an imbricated and inverted mafic/ultramafic allochthon. This was subsequently folded and intruded by granitoids during younger tectonic events.

The Tokwe terrane is in many places unconformably overlain by a heterogeneous assemblage of volcanic and sedimentary rocks known as the Lower Greenstones. In the Belingwe greenstone belt this Lower Greenstone assemblage is called the Mtshingwe Group, composed of mafic, ultramafic, intermediate and felsic volcanic rocks, pyroclastic deposits, and a wide variety of sedimentary rocks. Isotopic ages on these rocks range from 2.9 to 2.83 billion years, and the rocks are intruded by the 2.83 billion-year-old Chingezi tonalite. The Lower Greenstones are also well developed in the Midlands (Silobela), Filabusi, Antelope–Lower Gwanda, Shangani, Bubi, and Gweru-Mvuma greenstone belts. The upper part of the Lower Greenstones has yielded U-Pb ages of 2.8 billion years in the Gweru greenstone belt, and 2.79 billion years in the Filabusi belt.

The Buhwa and Mweza greenstone belts contain the thickest section of 3 billion-year-old shallow-water sedimentary rocks in the Zimbabwe craton. The Buhwa belt contains a western shelf succession and an eastern deeper water basinal facies association. The shelf sequence is up to 2.5 miles (4 km) thick and includes units of quartzite and quartz sandstone, shale, and iron formation, whereas the eastern deep-water association consists of strongly deformed shales, mafic-ultramafic lavas, chert, iron formation, and possible carbonate rocks. The Buhwa greenstone belt is intruded by the Chipinda batholith, which has an estimated age of 2.9 billion years. Shelf-facies rocks may have originally extended along the southeastern margin of the Tokwe terrane into Botswana, where a similar assemblage is preserved in the Matsitama greenstone belt. Rocks of the Matsitama belt include interlayered quartzites, iron formations, marbles and metacarbonates, and quartzofeldspathic gneisses in a 6–12 mile (10–20 km) thick structurally imbricated succession. The strong penetrative fabric in this belt may be related to deformation associated with the formation of the Limpopo belt to the south, but early nappes and structural imbrication that predate the regional cleavage-forming event are also recognized. The Matsitama belt (Mosetse Complex) is separated from the Tati belt to the east by an accretionary gneiss terrane (Motloutse Complex) formed during convergence of the two crustal fragments. The Tati and Vumba greenstone belts (Francistown granite-greenstone complex) were overturned before penetrative deformation, possibly indicating that they represent lower limbs of large regional nappe structures. The mafic, oceanic-affinity basalts of the Tati belt are overlain by andesites and other silicic igneous rocks, and intruded by syn-tectonic granitoids, typical of magmatic arc deposits. Similar arc-type rocks occur in the lower Gwanda greenstone belts to the east. The Lower Gwanda and Antelope greenstone belts are allochthonously overlain by basement gneisses thrust over the greenstones prior to granite emplacement.

A second sequence of sedimentary rocks lies unconformably over the Lower Greenstone assemblage and overlaps onto basement gneisses in several greenstone belts, most notably in the Belingwe belt, where the younger sequence is known as the Manjeri Formation. The Manjeri Formation contains conglomerates and shallow-water sandstones and locally carbonates at the base, and ranges stratigraphically up into cherts, argillaceous beds, graywacke, and iron formation. The top of the Manjeri Formation is marked by a regional fault. The Manjeri Formation is between 800 and 2,000 feet (250–600 m) thick along most of the eastern side of the Belingwe belt, except where it is cut out by faulting, and it thins northward to zero meters north of Zvishavane. It is considerably thinner on the western edge of the belt. On the scale of the Belingwe belt, the Manjeri Formation thickens toward the southeast, with some variation in structural thickness attributed to either sedimentary or tectonic ramping. The age of the Manjeri Formation is poorly constrained and may be diachronous across strike. However, the Manjeri Formation must be younger than the unconformably underlying circa 2.8 billion-year-old Ga Lower Greenstones, and it must be older than or in part contemporaneous with the thrusting event that emplaced circa 2.7 billion-year-old magmatic rocks of the Upper Greenstones over the Manjeri Formation. The Manjeri Formation overlaps onto the gneissic basement of the Tokwe terrane on the eastern side of the Belingwe belt, and at Masvingo, and rests on older (3.5 billion-year-old Sebakwian Group) greenstones at Shurugwi. Regional stratigraphic relationships suggest that the Manjeri Formation forms a southeast-thickening sedimentary wedge that prograded onto the Tokwe terrane.

Northern Belt (Zwankendaba Arc)

The northern volcanic terrane includes the Harare (Salisbury), Mount Darwin, Chipuriro (Sipolilo), Midlands (Silobela and Que Que), Chegutu (Gatoma), Bubi, Bulawayo, and parts of the Filabusi and Gwanda greenstone belts. These contain a lower volcanic series overlain by a calc-alkaline suite of basalts, andesites, dacites, and rhyolites. Pyroclastic, tuffaceous, and volcaniclastic horizons are common. Also common are iron formations, and other sedimentary rocks including slates, phyllites, and conglomerate. In the Bulawayo-Silobela area (Mulangwane Range), the top of the upper volcanics include a series of porphyritic and amgdaloidal andesitic and dacitic agglomerate and other pyroclastic rocks.

U-Pb ages from felsic volcanics of the northern volcanic belt include 2.696, 2.698, 2.683, 2.702, and 2.697 billion years. Isotopic data from the Harare-Shamva greenstone belt and surrounding granitoids suggest that the greenstones evolved on older continental crust between 2.715 and 2.672 billion years ago. The age of deformation is constrained by a 2.667 billion-year-old syn-tectonic gneiss, a 2.664 billion-year-old late syn-tectonic intrusion, and 2.659 billion-year-old shear zone-related gold mineralization. Other posttectonic granitoids yielded U-Pb zircon ages of 2.649, 2.618, and 26.01 billion years. Isotopic data for the felsic volcanics suggest that the felsic magmas were derived from a melt extracted from the mantle 200 million years before volcanism and saw considerable interaction between these melts and older crustal material.

Southern Belt

The southern belt of tholeiitic mafic-ultramafic–dominated greenstones structurally overlies shallow-water sedimentary sequences and gneissic rocks in parts of the Belingwe, Mutare (Umtali), Masvingo (Fort Victoria), Buhwa, Mweza, Antelope, and Lower Gwanda belts. The most extensively studied of these is the Belingwe belt, which many workers have used as a stratigraphic archetype for the entire Zimbabwe craton. The allochthonous Upper greenstones are here discussed separately from the structurally underlying rocks of the Manjeri Formation that rest unconformably on Tokwe terrane gneissic rocks.

The Archean Belingwe greenstone belt in southern Zimbabwe has proven to be one of the most important Archean terranes for testing models for the early evolution of the Earth and the formation of continents. It has been variously interpreted to contain a continental rift, arc, flood basalt, and structurally emplaced ophiolitic or oceanic plateau rocks. It is a typical Archean greenstone belt, being an elongate belt with abundant metamorphosed mafic rocks and metasediments, deformed and metamorphosed at greenschist to amphibolite grade. The basic structure of the belt is a refolded syncline, although debate has focused on the significance of early folded thrust faults.

The 3.5 billion-year-old Shabani-Tokwe gneiss Complex forms most of the terrain east of the belt and underlies part of the greenstone belt. The 2.8–2.9 billion-year-old Mashaba tonalite and Chingezi gneiss are located west of the belt. These gneissic rocks are overlain unconformably by a 2.8 billion-year-old group of volcanic and sedimentary rocks known as the Lower Greenstones or Mtshingwe Group, including the Hokonui, Bend, Brooklands, and Koodoovale Formations. These rocks, and the eastern Shabani-Tokwe gneiss, are overlain unconformably by a shallow water sedimentary sequence known as the Manjeri Formation, consisting of quartzites, banded iron formation, graywacke, and shale. A major fault is located at the top of the Manjeri Formation, and the Upper Greenstones structurally overlie the lower rocks being everywhere separated from them by this fault. The significance of this fault, whether a major tectonic contact or a fold accommodation–related structure, has been the focus of considerable scientific debate. The 2.7 billion-year-old Upper Greenstones, or the Ngezi Group, includes the ultramafic-komatiitic Reliance Formation, the four-mile (6-km) thick tholeiitic pillow lava–dominated Zeederbergs Formation, and the sedimentary Cheshire Formation. All of the units are intruded by the 2.6 billion-year-old Chibi granitic suite.

The Lower Greenstones have been almost universally interpreted to be deposits of a continental rift or rifted arc sequence. However, the tectonic significance of the Manjeri Formation and Upper Greenstones has been debated. The Manjeri Formation is certainly a shallow-water sedimentary sequence that rests unconformably over older greenstones and gneisses. Correlated with other shallow-water sedimentary rocks across the southern craton, it may represent the remnants of a passive-margin type of sedimentary sequence.

Geochemical studies have suggested that the komatiites of the Reliance Formation in Belingwe could not have been erupted through continental crust, but rather that they are similar to intraplate basalts and distinct from midocean ridge and convergent margin basalts. The geochemistry of the Ngezi Group in the Belingwe greenstone belt suggests that it could be a preserved oceanic plateau and that there was no evidence for them to have been derived from a convergent margin.

The top of the Manjeri Formation is marked by a fault, the significance of which has been disputed. Some scientists have suggested that it may be a fault related to the formation of the regional syncline, formed in response to the rocks in the center of the belt being compressed and moving up and out of the syncline. Work on the sense of movement on the fault zone, however, shows that the movement sense is incompatible with such an interpretation, and that the fault is a folded thrust fault that placed the Upper Greenstones over the Manjeri Formation. Therefore, the tectonic setting of the Upper Greenstones is unrelated to the rocks under the thrust fault, and the Upper Greenstones likely were emplaced from a distant location. The overall sequence of rocks in the Upper Greenstones, including several kilometers of mafic and ultramafic lavas, is very much like rock sequences found in contemporary oceanic plateaus or thick oceanic crust, and such an environment seems most likely for the Upper Greenstones in Belingwe and other nearby greenstone belts of the Zimbabwe craton.

Cratonwide Overlap Assemblage (Shamvaian Group)

The Shamvaian Group consists of a sequence of coarse clastic rocks that overlie the Upper Greenstones in several locations. These conglomerates, arkoses, and graywackes are well known from the Harare, Midlands, Masvingo, and Belingwe greenstone belts. The Cheshire Formation, the top unit of the Belingwe greenstone belt, consists of a heterogeneous succession of sedimentary rocks including conglomerate, sandstone, siltstone, argillite, limestone, cherty limestone, stromatolitic limestone, and minor banded iron formation. The Shamvaian Group is intruded by the circa 2.6 billion-year-old Chilimanzi Suite granites, providing an upper age limit on deposition. In the Bindura-Shamva greenstone belt the Shamvaian Group is 1.2 miles (2 km) thick, beginning with basal conglomerates and grading up into a thick sandstone sequence. Tonalitic clasts in the basal conglomerate have yielded igneous ages of 3.2, 2.9, 2.8, and 2.68 billion years. Felsic volcanics associated with the Shamvaian Group in several greenstone belts have ages of 2.66 to 2.64 billion years.

Chilimanzi Suite

The Chilimanzi suite of K-rich granitoids is one of the last magmatic events in the Zimbabwe craton, with reported ages of 2.57 to 2.6 billion years. These granites appear to be associated with a system of large intracontinental shear zones that probably controlled their position and style of intrusion. These relatively late structures are related to north-northwest to south-southeast shortening and associated southwestward extrusion of crust during the continental accretion and collision as recorded in the Limpopo belt.

Accretion of the Archean Zimbabwe Craton

The oldest part of the Zimbabwe craton, the Tokwe terrane, preserves evidence for a complex series of tectonomagmatic events ranging in age from 3.6 to 2.95 billion years ago. These events resulted in complex deformation of the Sebakwian greenstones and intervening gneissic rocks. This may have involved convergent margin accretionary processes that led to the development of the Tokwe terrane as a stable continental nuclei by 2.95 billion years ago.

A widespread unit of mixed volcanic and sedimentary rocks was deposited on the Tokwe terrane at circa 2.9 billion years ago. These lower greenstones include mafic and felsic volcanic rocks, coarse conglomerates, sandstones, and shales. The large variation in volcanic and sedimentary rock types, along with the rapid and significant lateral variations in stratigraphic thicknesses that typify the Lower Greenstones, are characteristic of rocks deposited in continental rift or rifted arc settings. The Tokwe terrane was subjected to rifting at 2.9 Ga, leading to the formation of widespread graben in which the Lower Greenstones were deposited. The southeastern margin of the Tokwe terrane may have been rifted from another, perhaps larger fragment at this time, along a line extending from the Buhwa-Mweza greenstone belts to the Mutare belt, allowing a thick sequence of passive margin–type sediments (preserved in the Buwha greenstone belt) to develop on this rifted margin. Age constraints on the timing of the passive margin development are not good, but appear to fall within the range of 3.09 to 2.86 billion years ago. By 2.7 billion years ago, a major marine transgression covered much of the southern half of the Tokwe terrane, as recorded in shallow-water sandstones, carbonates, and iron formations of the Manjeri-type units preserved in several greenstone belts. The Manjeri-type units overlap the basement of the Tokwe terrane in several places (e.g., Belingwe, Masvingo), and lie unconformably over the circa 3.5 and 2.9 billion-year-old greenstones. Regional stratigraphic relationships suggest that the Manjeri Formation forms a southeast thickening sedimentary wedge that prograded onto the Tokwe terrane, in a manner analogous to the Ocoee-Chilhowee and correlative Sauk Sequence shallow-water progradational sequence of the Appalachians, and similar sequences in other mountain ranges. The progradation could have been driven by sedimentary or tectonic flexural loading of the margin of the Tokwe terrane, but most evidence points to the latter cause. The top of the Manjeri-type units represents a regional detachment surface, on which allochthonous units of the southern greenstones were emplaced. Loading of the passive margin by these thrust sheets would have induced flexural subsidence and produced a foreland basin that migrated onto the Tokwe terrane.

The 2.7 billion-year-old greenstones are divided into a northwestern arc-like succession, and a southeastern allochthonous succession. The northwestern arc succession contains lavas with strong signatures of eruption through older continental crust, and the arc appears to be a continental margin type of magmatic province. In contrast, the southern greenstones are allochthonous and were thrust in place along a shear zone that is well exposed in several places, including the Belingwe belt. These southern greenstones have a stratigraphy reminiscent of thick oceanic crust, suggesting that they may represent an oceanic plateau that was obducted onto the Tokwe terrane 2.7 billion years ago. All of the southern greenstones are distributed in a zone confined to about 100 miles (150 km) from the line of passive margin-type sediments extending from Mweza-Buhwa to Mutare. This "Umtali line" may represent the place where an ocean or back arc basin opened between 2.9 and 2.8 billion years ago, then closed at 2.7 billion years, and forms the root zone from which the southern greenstones were obducted. This zone contains numerous northeast-striking mylonitic shear zones in the quartzofeldspathic gneisses. Closure of the Sea of Umtali at circa 2.7 billion years ago deposited a flysch sequence of graywacke-argillite turbidites that forms the upper part of the Manjeri Formation, and formed a series of northeast-striking folds.

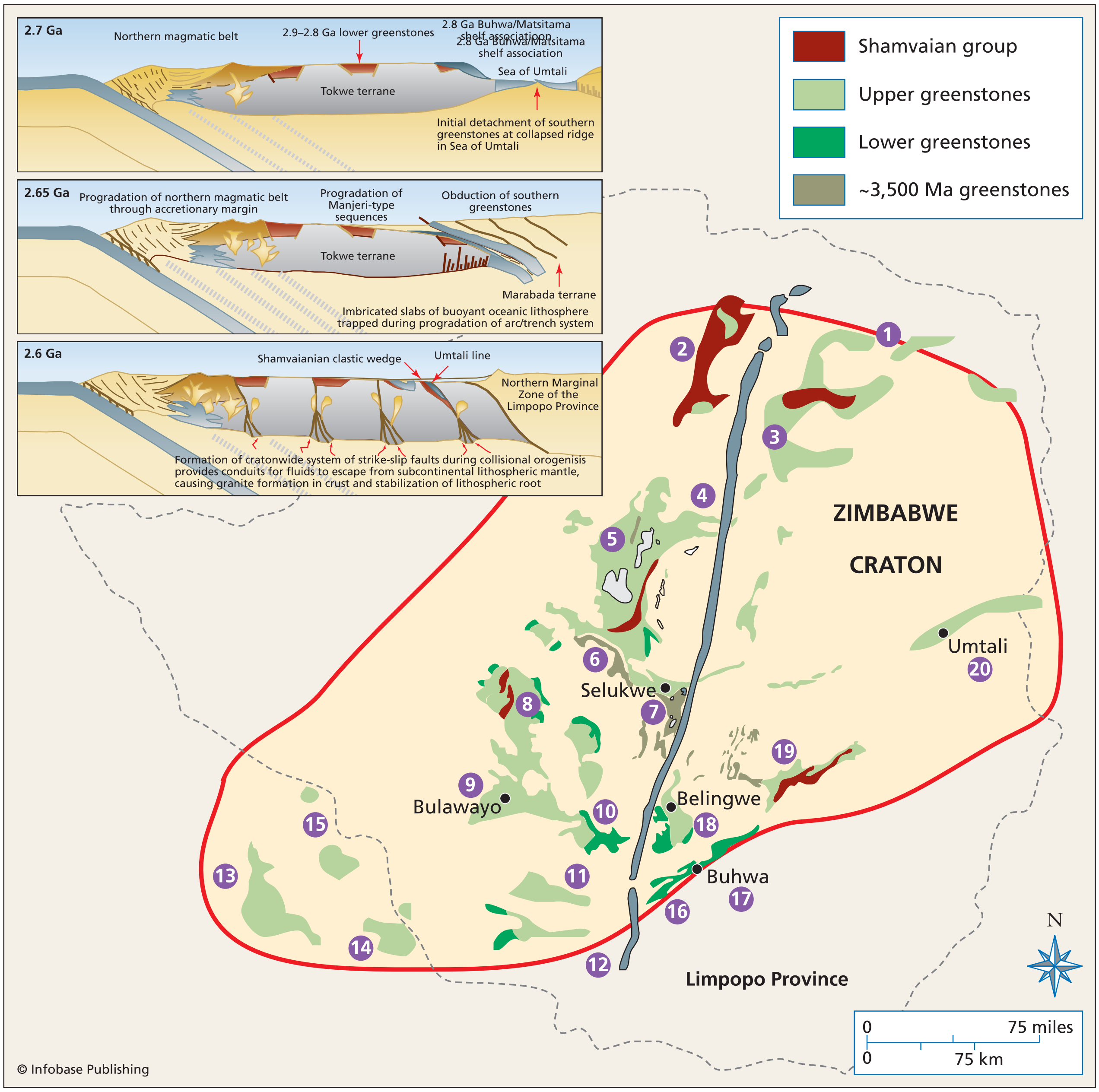
The latest Archean tectonic events to affect the Zimbabwe craton is associated with deposition of the Shamvaian group, and intrusion of the Chilimanzi suite granitoids at circa 2.6–2.57 billion years ago. These events appear to be related to a collision of the now-amalgamated Zimbabwe craton with northern Limpopo Province, as the Zimbabwe and Kaapvaal cratons collided. Interpretations of the Limpopo orogeny suggest that the Central Zone of the Limpopo Province collided with the Kaapvaal craton at circa 2.68 billion years ago, and that this orogenic collage collided with the southern part of the Zimbabwe craton at 2.58 billion years ago. Deposition of the Shamvaian Group clastic sediments occurred in a foreland basin related to this collision, and the intrusion of the Chilimanzi suite occurred when this foreland became thickened by collisional processes, and was cut by sinistral intracontinental strike-slip faults. Late folds in the Zimbabwe craton are oriented roughly parallel to the collision zone, and appear contemporaneous with this collision. The map pattern of the southern Zimbabwe craton shows some interference between folds of the early generation (related to the closure of the Sea of Umtali) and these late folds related to the Limpopo orogeny.

CONGO CRATON

The Congo craton includes a generally poorly known and underexplored region of Archean rocks that are exposed around the Congo basin in central Africa. The craton extends from the Kasai region of the Democratic Republic of the Congo into Sudan, Angola, Zambia, Gabon, and Cameroon, and is known for containing many greenstone belts, albeit deeply weathered under thick profiles of laterite soil. Most parts of the Congo craton are known from separate regions that outcrop around the Congo basin, and these areas are generally known as cratons or blocks, even though they are likely continuous at depth.

The Kasai (and northeast Angolan) block is exposed over an area 270 miles (450 km) across by 210 miles (350 km) north-south in Kasai, Democratic Republic of the Congo, Lunda, and Angola. The area is overlain by a thick Phanerozoic cover, so most of the Archean rocks are restricted to river valleys. The Archean rocks are divided into three main divisions, including the circa 3.4 billion-year-old Luanyi tonalitic-granodioritic gneiss; two belts of younger, strongly metamorphosed (granulite facies) rocks; and a still younger granitoid and migmatite complex known as the Dibaya Complex. The age of the granulite facies events are constrained to be between 2.77 and 2.84 billion years, with a lower pressure and temperature (retrogressive) metamorphic event at 2.68 billion years ago. The late-stage Dibaya Complex includes calc-alkaline granites and gneisses that are strongly deformed and mylonitized locally, with deformation and migmatization at 2.68 billion years ago. These different assemblages are cut by the undeformed circa 2.59 Ga Malafundi granites.

The Gabon-Chaillu block consists of two roughly elliptical areas each a couple of hundred miles (several hundred km) across, in Cameroon,



Map of the Zimbabwe craton showing the distribution of the old gneissic Tokwe terrane, the northern and southern magmatic belts, and shelf-type associations. Numbers correspond to individual greenstone belts: 1 Mount Darwin, 2 Chipuriro, 3 Harare, 4 Chegutu, 5 Midlands, 6 Gweru-Mvuma, 7 Shurugwe, 8 Bubi, 9 Bulawayo, 10 Filabusi, 11 Gwanda, 12 Antelope, 13 Lower Gwanda, 14 Tati, 15 Vumba, 16 Mweza, 17 Buhwa, 18 Belingwe, 19 Masvingo, 20 Mutare. Inset is a tectonic cross section showing evolution of the Zimbabwe craton, with the northern magmatic belt evolving as an Andean-style arc above a major subduction zone from 2.7 to 2.6 billion years ago, while the southern magmatic belts represent where a small ocean basin closed in the same interval.

Equatorial Guinea, Gabon, and Congo. Rocks in this block include an assemblage of 2.8–3.2 billion-year-old charnockite, migmatite, gneiss, greenstone belts, and late-stage 2.7 billion-year-old granitoid plutons. Greenstone belts in the block include complexly folded pillow basalts, rhyolites, quartzite, and banded iron formation, in structural contact with granitoid gneiss and granodiorite. High-grade metamorphism occurred at 2.9 Ga, corresponding to other high-grade metamorphic events known across central Africa. Much of the northern part of the block was reworked by strong northeast-trending folds, faults, and regional metamorphism at 500 million years ago, in a part of the Central African belt, related to the late Proterozoic–early Paleozoic amalgamation of the supercontinent of Gondwana.

The Kibalian block covers an area about 500 miles (800 km) long by 300 miles (500 km) wide in northern Zaire and the southern Central African Republic, to Lake Mobutu in Uganda. The Kibale and Uele Rivers flow across the block, providing good exposures of the basement rocks. The block is bordered in the north by folded Late Proterozoic rocks, by the West Nile gneiss Complex on the west, and on the south by strata of the Congo basin. The Kibalian block contains a granite-greenstone assemblage, with granitoids falling into three groups. An older tonalite-trondhjemite-granodiorite group (TTG) has an age of 2.8 billion years, and younger granites have been dated to be 2.5 billion years old.

The greenstone and schist belts form structurally complex assemblages of mafic schists, intruded by 2.9 billion-year-old tonalites. Of the 11 major greenstone belts, most have a similar rock assemblage, including the lower Kibalian sequence, consisting of mafic to intermediate volcanic rocks and banded iron formation, overlain by the upper Kibalian sequence, consisting of andesite, quartzite, and banded iron formation. At Mambasa the lower Kibalian sequence is thought to overlie unconformably the 3.35 Ga Ituri metasedimentary-rich basement gneiss, and is in turn intruded by the 2.5 Ga old Mambasa granite.

A 600 × 300–mile (1,000 × 500–km) area on the central plateau of Tanzania and east of Lake Victoria is known as the Tanzania block. The southeastern part of the block near Dodoma contains mainly granitoids and migmatitic gneisses, with remnants of schist or greenstone belts. These schist belts contain assemblages of quartzite, banded iron formation, schists that locally bear corundum, amphibolite, and mafic and ultramafic gneiss. The granitoid gneisses are about 2.6 billion years old, and the craton is intruded by circa 1.8 Ga late-stage granites. Kimberlite pipes locally bring up fragments of older, circa 3.1 Ga gneiss, the oldest rocks recognized in the Tanzania block. Schist belts in the central plateau region of Tanzania are very similar to the schist belts of southeast Uganda, and this forms the basis of correlating the Tanzania and Kibalian blocks as part of the larger Congo craton.

WEST AFRICAN CRATON

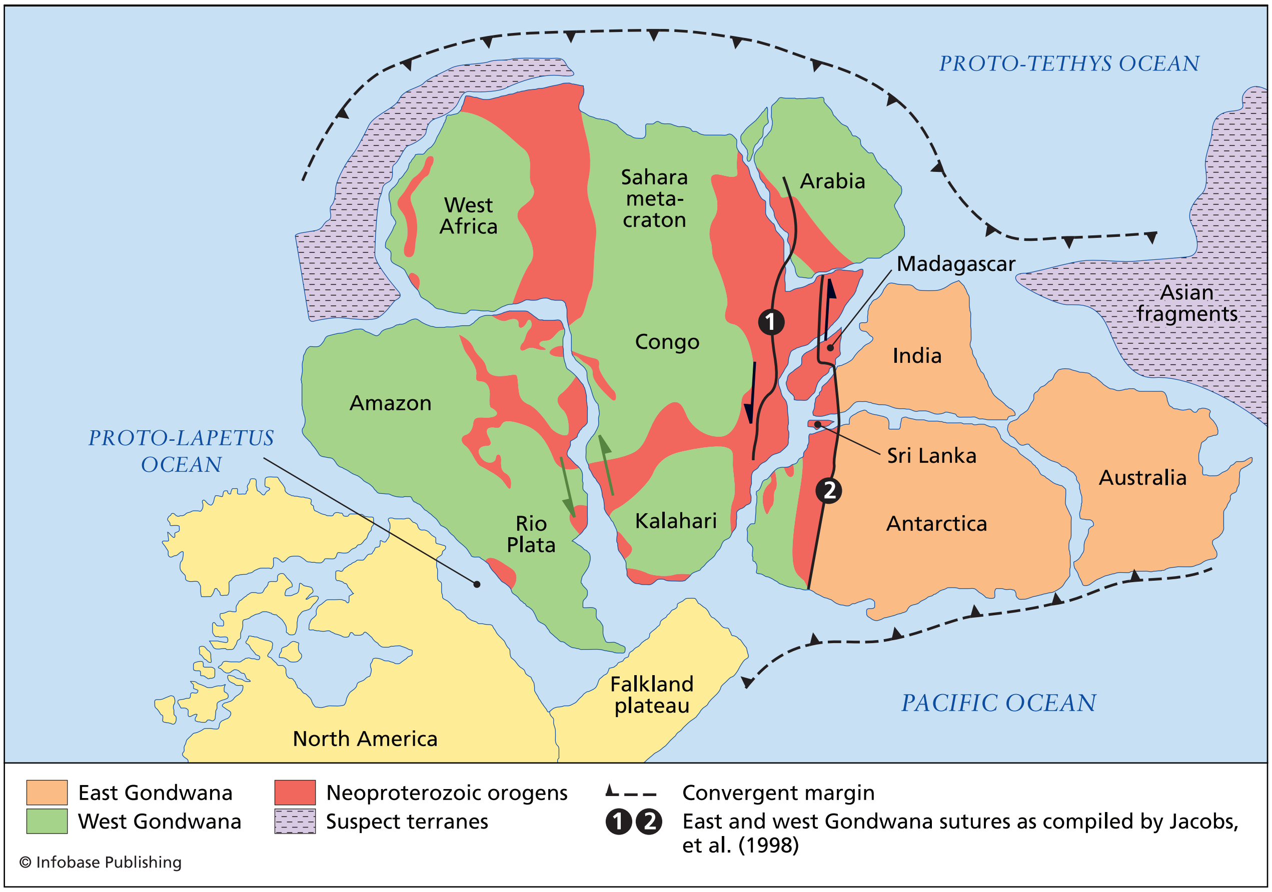
Archean rocks form large sections of the basement rocks between the Gulf of Guinea and the Atlas Mountains. These rocks form parts of the Man and Reguibat shields of the West African craton, and parts of the Tuareg shield.

The Man shield forms the southern part of the West African craton along the Gulf of Guinea and includes the Archean Liberian (Kenema-Man) domain in the west and the Eburnean (Baoule-Mossi) domain in the east. The Liberian domain occupies most of Sierra Leone, Liberia, Guinea, Ivory Coast, and part of Guinea Bissau. Rocks in this domain include many structurally complex greenstone remnants consisting of ultramafic rocks, mafic volcanic rocks and banded iron formations, granitoid gneiss, and granites, forming a classical granite-greenstone terrain. Some of the gneisses have been dated to be 3.2–3.0 billion years old, whereas the greenstones are intruded by granites that are 2.7 billion years old. Greenstone belts in the west are generally metamorphosed to amphibolite facies, comparatively large, being up to 80 miles (130 km) long, and up to 4 miles (6.5 km) in structural thickness. Greenstone belts in the southeast are smaller, being up to 25 miles (40 km) long, thinner, and show a wide range of metamorphic grades from greenschist to granulite facies. Greenstone belts in the east have more quartzite and pelite than those in the west, and are structurally discordant with basement gneiss and granitoids. Structures across the Man shield generally strike northerly and formed in a strong tectonic event at 2.75 billion years ago, known as the Liberian orogeny, that is superimposed on structures from an older event, known as the Leonean orogeny.

The westernmost part of the Man shield consists of three narrow belts of Proterozoic-Paleozoic tectonic activity, known as the Rokelides. Conglomerates, sandstones, arkose, and volcanic rocks of the Rokell River Group unconformably overlie the older Kenema basement and are increasingly deformed and metamorphosed to the west. The western margin of the Rokell River Group is marked by large thrusts where recumbently folded klippen of intensely deformed and metamorphosed sedimentary and volcanic rocks of the late Archean-Proterozoic Marampa Group were thrust to the east over the Man shield. Farther west, a 180-mile (300-km) long belt of granulite facies Archean metasedimentary rocks of the Kasila Group represent the core of a deeply eroded orogen. The eastern boundary of the Kasila Group is a 3-mile (5-km) wide mylonite belt, interpreted as an Archean suture that formed when the West African craton collided with the Guiana shield of South America.

PAN-AFRICAN BELTS AND THE EAST AFRICAN OROGEN

The East African Orogen encompasses the Arabian-Nubian shield in the north and the Mozambique belt in the south. These and several other orogenic



Map of the East African orogen and other Pan-African belts that formed as ocean basins closed to form the supercontinent of Gondwana *(modeled from T. Kusky, M. Abdelsalam, R. Tucker, and R. Stern, 2003)*

belts are commonly referred to as Pan-African belts, recognizing that many distinct belts in Africa and other continents experienced deformation, metamorphism, and magmatic activity in the general period of 800–450 Ma. Other definitions of the Pan-African orogens are more restrictive, and consider them to be confined to a complex collisional system between the Congo and Kalahari cratons in this time interval, thus including in Africa the Gareip belt, the Kaoko belt, Damara orogen, Lufilian arc, Zambezi belt, Malawi orogen, Mozambique belt, and Luria arc. Pan-African tectonothermal activity in the Mozambique belt was broadly contemporaneous with magmatism, metamorphism, and deformation in the Arabian-Nubian shield, and the two are broadly equivalent. The difference in lithology and metamorphic grade between the two belts has been attributed to the difference in the level of exposure, with the Mozambican rocks interpreted as lower crustal equivalents of the rocks in the Arabian-Nubian shield. Neoproterozoic closure of the Mozambique Ocean collapsed an accretionary collage of arc and microcontinental terranes and sutured east and west Gondwana along the length of the East African orogen.

The formation of Gondwana at the end of the Precambrian and the dawn of the Phanerozoic by the collision of cratons including the Congo, Kalahari, India, Antarctica, and South American blocks represents one of the most fundamental problems being studied in earth sciences today. Studies of Gondwana link many different fields, and there are currently numerous and rapid changes in understanding of events related to the assembly of Gondwana. One of the most fundamental and most poorly understood aspects of the formation of Gondwana is the timing and geometry of closure of the oceanic basins that separated the continental fragments that amassed to form the Late Proterozoic supercontinent. Final collision between East and West Gondwana most likely occurred during closure of the Mozambique Ocean, forming the East African orogen.

Recent geochronologic data indicate the presence of two major "Pan-African" tectonic events within East Africa. The East African Orogeny (800–

650 Ma) represents a distinct series of events within the Pan-African of central Gondwana, responsible for the assembly of greater Gondwana. Collectively, paleomagnetic and age data indicate that another later event at 550 Ma (Kuunga Orogeny) may represent the final suturing of the Australian and Antarctic segments of the Gondwana continent.

ATLAS MOUNTAINS

The Atlas Mountains are a series of mountains and plateaus in northwest Africa extending about 1,500 miles (2,500 km) in southwest Morocco, northern Algeria, and northern Tunisia. The highest peak in the Atlas is Jabel Toubkal, at 13,665 feet (4,168 m) in southwest Morocco. The Atlas Mountains are dominantly folded sedimentary rocks uplifted in the Jurassic, and related to the Alpine system of Europe. The Atlas consists of several ranges separated by fertile lowlands in Morocco, from north to south including the Rif Atlas, Middle Atlas, High Atlas (Grand Atlas), and Anti Atlas. The Algerian Atlas consists of a series of plateaus including the Tell and Saharan Atlas rimming the Chotts Plateau, then converging in Tunisia. The Atlas form a climatic barrier between the Atlantic and Mediterranean basins and the Sahara, with rainfall falling on north-facing slopes but arid conditions dominating on the rain-shadow, south-facing slopes. The Atlas are rich in mineral deposits including coal, iron, oil, and phosphates. The area is also used extensively for sheep grazing, with farming in the more fertile intermountain basins.

EAST AFRICAN RIFT SYSTEM

Extensional plate tectonic forces are presently breaking Africa apart, with parts of eastern Africa rifting away from the main continent. The rift valley that separates these two sections is known as the East African rift system, or the Great Rift Valley, extending from the Ethiopian Afar region, through two segments known as the eastern and western rifts that bend around Lake Victoria, then extend to the Mozambique Channel.

The Main Ethiopian and North-Central Afar rifts are part of the continental East African rift system. These two kinematically distinct rift systems, typical of intracontinental rifting, are at different stages of evolution. In the north and east the continental rifts meet the oceanic rifts of Red Sea and Gulf of Aden, respectively, both of which have propagated into the continent. Seismic refraction and gravity studies indicate that the thickness of the crust in the Main Ethiopian rift is less than or equal to 18.5 miles (30 km). In Afar the thickness varies from 14 to 16 miles (23–26 km) in the south and to 8.5 miles (14 km) in the north. The plateau on both sides of the rift

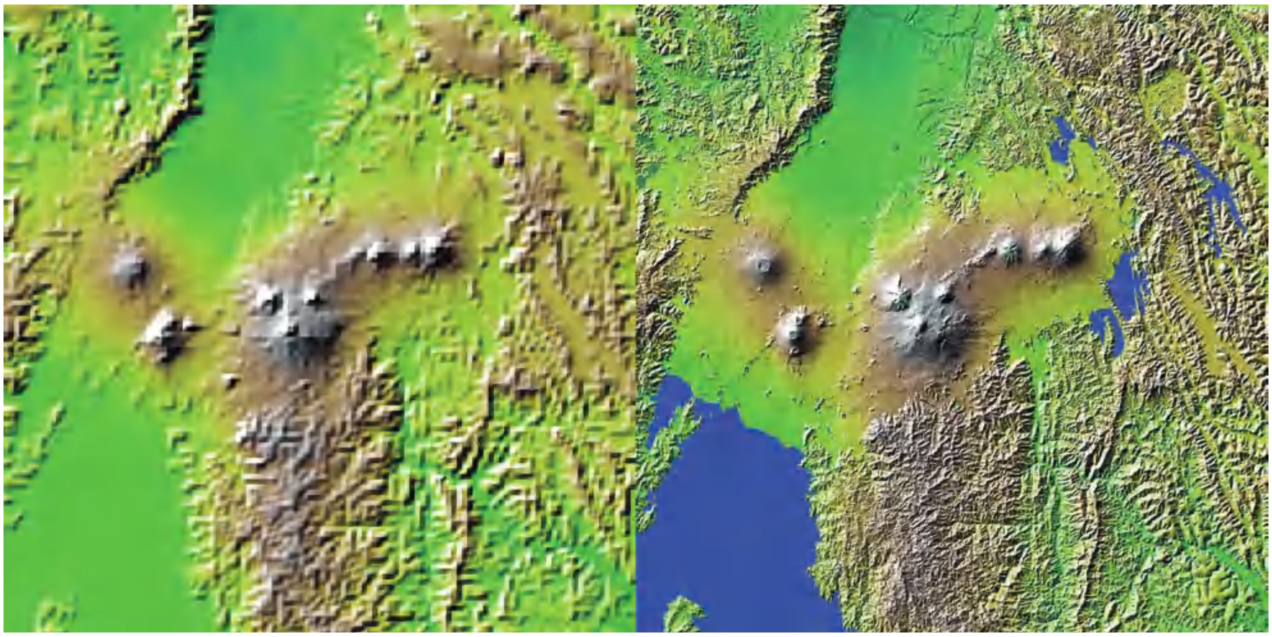


Image of digital elevation model of East African Rift at Lake Kivu from data generated by Shuttle Radar Topography Mission. Area shown covers parts of the Democratic Republic of the Congo, Rwanda, and Uganda. Elevation is color coded, progressing from green at lower elevations through yellow to brown at higher elevations. A false sun in the NW (upper left, pixelated area) causes topographic shading. Lake Kivu lies in the East African Rift, which forms a smooth lava and sediment–filled trough in the area. Two volcanic complexes are shown in the rift, including the Nyiragongo volcano (the one closer to the lake), which erupted in 2002. Virunga volcanic chain extends east of the rift.

has a crustal thickness of 21.5–27 miles (35–44 km). Geologic and geodetic studies indicate separation rates of 0.1–0.2 inches (3–6 mm) per year across the northern sector of the Main Ethiopian rift between the African and Somali plates. The rate of spreading between Africa and Arabia across the North-Central Afar rift is relatively faster, about 0.8 inches (20 mm) per year. Paleomagnetic directions from Cenozoic basalts on the Arabian side of the Gulf of Aden indicate seven degrees of counterclockwise rotation of the Arabian plate relative to Africa, and clockwise rotations of up to 11 degrees for blocks in eastern Afar. The initiation of extension on both sides of the southernmost Red Sea rift, Ethiopia, and Yemen appear coeval, with extension starting between 22 and 29 million years ago.

The Ethiopian Afar region is one of the world's largest, deepest regions below sea level that is subaerially exposed on the continent, home to some of the earliest known hominid fossils. The Afar is a hot, arid region where the Awash River drains northward out of the East African rift system, and is evaporated in Lake Abhe before it reaches the sea. This unique and spectacular region is located in eastern Africa in Ethiopia and Eritrea, between Sudan, Somalia, and across the Red Sea and Gulf of Aden from Yemen. The region is so topographically low because it is located at a tectonic triple junction, where three main plates are spreading apart, causing regional subsidence. The Arabian plate is moving northeastward away from the African plate, and the Somali plate is moving, at a much slower rate, to the southeast away from Africa. The southern Red Sea and north-central Afar Depression form two parallel north-northwest-trending rift basins, separated by the Danakil Horst, related to the separation of Arabia from Africa. Of the two rifts, the Afar depression is exposed at the surface, whereas the Red Sea rift floor is submerged below the sea. The north-central Afar rift is complex, consisting of many grabens and horsts. The Afar Depression merges southward with the northeast-striking Main Ethiopian rift, and eastward with the east-northeast-striking Gulf of Aden. The Ethiopian Plateau bounds it on the west. Pliocene volcanic rocks of the Afar stratoid series and the Pleistocene to recent volcanics of the Axial Ranges occupy the floor of the Afar Depression. Miocene to recent detrital and chemical sediments are intercalated with the volcanics in the basins.

South of the Ethiopian rifts, the eastern branch of the main East African rift strikes southward through Kenya, forming Lake Turkana across the Kenya highlands, and forming the famous Ngorongoro crater, where millions of wildlife gather for scarce water in the deep rift valley. The western branch of the main East Africa rift strikes southward from Ethiopia and Sudan into Uganda, forming a series of deep, steep-sided lakes including Lakes Albert, Edward, Kivu, Tanganyika, and Malawi. Some of these lakes are more than a mile (1.6 km) deep, and are fed by drainage systems that remain on the floor of the rift, while drainage on the rift shoulders carries water away from the central rift.

See also ARCHEAN; BASIN, SEDIMENTARY BASIN; CONVERGENT PLATE MARGIN PROCESSES; CRATON; DEFORMATION OF ROCKS; DESERTS; DIVERGENT PLATE MARGIN PROCESSES; GREENSTONE BELTS; MADAGASCAR; OROGENY; PRECAMBRIAN.

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Andes Mountains The Andes are a 5,000-mile (8,000-km) long mountain range in western South America, running generally parallel to the coast, between the Caribbean coast of Venezuela in the north and Tierra del Fuego in the south. The mountains merge with ranges in Central America and the West Indies in the north, and with ranges in the Falklands and Antarctica in the south. Many snow-covered peaks rise more than 22,000 feet (6,000 m), making the Andes the second-tallest mountain belt in the world, after the Himalayan chain. The highest range in the Andes is the Aconcauga on the central and northern Argentine-Chilean border. The high, cold Atacama desert is located in the northern Chile sub-Andean range, and the high Altiplano Plateau is situated along the great bend in the Andes in Bolivia and Peru.

The southern part of South America consists of a series of different terranes (belts of distinctive rocks) added to the margin of the supercontinent of Gondwana in late Proterozoic and early Proterozoic times. Subduction and the accretion of oceanic terranes continued through the Paleozoic, forming a 155-mile (250-km) wide accretionary wedge. The Andes developed as a continental margin volcanic arc system on the older accreted terranes, formed above a complex system of subducting plates from the Pacific Ocean. They are geologically young, having been uplifted mainly in the Cretaceous and Tertiary (roughly the past 100 million years), with active volcanism, uplift, and earthquakes. The specific nature of volcanism, plutonism, earthquakes, and uplift are found to be strongly segmented in the Andes, and related to the nature of the subducting part of the plate, including its dip and age. Regions above places where the subducting plate dips more than 30 degrees have active volcanism, whereas regions above places where the subduction zone is subhorizontal do not have active volcanoes.

Alpamayo Peak in the Cordilleras Mountains, Peruvian Andes *(Galyna Andrushko, Shutterstock, Inc.)*

The Altiplano is a large, uplifted plateau in the Bolivian and Peruvian Andes of South America. The plateau has an area of about 65,536 square miles (170,000 km^2), and an average elevation of 12,000 feet (3,660 m) above sea level. The Altiplano is a sedimentary basin caught between the mountain ranges of the Cordillera Oriental on the east and the Cordillera Occidental on the west. The Altiplano is a dry region with sparse vegetation, and scattered salt flats. Villagers grow potatoes and grains, and a variety of minerals are extracted from the plateau and surrounding mountain ranges.

Lake Titicaca, the largest high-altitude lake navigable to large vessels in the world, is located at the northern end of the Altiplano. Sitting at 12,500 feet (3,815 m) above sea level, the lake straddles the border between Peru and Boliva. The lake basin is situated between Andean ranges on the Altiplano plateau, and is bordered to the northeast by some of the highest peaks in the Andes in the Cordillera Real, where several mountains rise to over 21,000 feet (6,400 m). Covering 3,200 square miles, Lake Titicaca is the largest freshwater lake in South America, although it is divided into two parts by the Strait of Tiquina. The body of water north of the strait is called Chucuito in Bolivia and Lake Grande in Peru, and south of the strait the smaller body of water is called Lake Huinaymarca in Bolivia and Lake Pequeno in Peru. Most of the lake is 460–600 feet (140–180 m) deep, but reaches 920 feet (280 m) deep near the northeast corner of the lake. The lake is fed by many short tributaries from surrounding mountains, and is drained by the Desaguadero River, which flows into Lake Poopo. However, only 5 percent of water loss is through this single outlet—the remainder is lost by evaporation in the hot, dry air of the Altiplano. Lake levels fluctuate on seasonal and several longer-time cycles, and the water retains a relatively constant temperature of 56°F (14°C) at the surface, but cools to 52°F (11°C) below a thermocline at 66 feet (20 m). Salinity ranges from 5.2–5.5 parts per thousand.

Lake Titicaca, translated variously as Rock of the Puma or Craig of Lead, has been the center of culture since pre-Inca times (600 years before present [b.p.]), and its shoreline is presently covered by Indian villages and terraced rice fields. Some of the oldest civilizations are preserved in ruins around Lake Titicaca, including those at Tiahuanaco, on the southern end of the lake, and others on the many islands in the lake. Ruins of a temple on Titicaca Island mark the spot where Inca legends claim that Manco Capac and Mama Ocllo, the founders of the Inca dynasty, were sent to Earth by the Sun.

The northern Andes are drained to the east by the world's second-longest river, the Amazon, stretching 3,900 miles (6,275 km) from the foothills of the Andes to the Atlantic Ocean. The southern Andes are drained to the east by the Paraná River, and a number of smaller rivers run down the steep western slope of the Andes to the Pacific Ocean. The Amazon begins where the Ucayili and Maranon tributaries merge, and drains into the Atlantic near the city of Belém. The Amazon carries the most water and has the largest discharge of any river in the world, averaging 150 feet (45 m) deep. Its drainage basin amounts to about 35 percent of South America, covering 2,500,000 square miles (6,475,000 km^2). The Amazon lowlands in Brazil include the largest tropical rain forest in the world. In this region the Amazon is a muddy, silt-rich river with many channels that wind around numerous islands in a complex maze. The delta region of the Amazon is marked by numerous fluvial islands and distributaries, as the muddy waters of the river get dispersed by strong currents and waves into the Atlantic. A strong tidal bore, up to 12 feet (3.7 m) high, runs up to 500 miles (800 km) upstream.

The Amazon River basin occupies a sediment-filled rift basin, between the Precambrian crystalline basement of the Brazil and Guiana shields. The area hosts economic deposits of gold, manganese, and other metals in the highlands, and detrital gold in lower elevations. Much of the region's economy relies on the lumber industry, with timber, rubber, vegetable oils, Brazil nuts, and medicinal plants sold worldwide.

Spanish commander Vincent Pinzon was probably the first European in 1500 to explore the lower part of the river basin, followed by the Spanish explorer Francisco de Orellana in 1540–41. Orellana's tales of tall, strong female warriors gave the river its name, borrowing from Greek mythology. Further exploration by Pedro Teixeira, Charles Darwin, and Louis Agassiz led to greater understanding of the river's course, peoples, and environment, and settlements did not appear until steamship service began in the middle 1800s.

See also CONVERGENT PLATE MARGIN PROCESSES; PLATE TECTONICS; SOUTH AMERICAN GEOLOGY.

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Antarctica The southern continent, Antarctica, is located nearly entirely below the Antarctic Circle (66° 33′ 39″) and is distributed asymmetrically around the south pole. The continent covers approximately 5.46 million square miles (14 million km^2), is nearly completely covered in ice, and has several large ice shelves extending off the mainland into surrounding oceans. Antarctica is surrounded by relatively isolated waters of the Southern Ocean, comprised of southern reaches of the Atlantic, Pacific, and Indian Oceans. Antarctica is the fifth-largest continent, covering an area equal to 57 percent of North America, or nearly 1.5 times the size of the United States including Alaska. The Russian explorers Mikhail Lazarev and Fabian Gottlieb von Bellingshausen first discovered the continent in 1820, and the Scottish cartographer John Bartholomew named it in 1890. In 1959 12 countries (later joined by more, to bring the total to 46) signed the Antarctic Treaty, prohibiting military activity and mining in Antarctica, and promoting cooperative scientific and environmental work.

The ice sheet covering Antarctica is the world's largest reservoir of fresh water (although frozen) and averages more than a mile (1.6 km) thick. The weight of this ice causes the underlying continent to be depressed by more than 1.5 miles (2.5 km). A small amount of rock is exposed in the Transantarctic Mountains and in the Dry Valleys area.

The Transantarctic Mountains divide the continent in two, stretching from the Ross Sea to the Wedell Sea. Western Antarctica (using the Greenwich meridian that runs nearly along the Transantarctic Mountains) is covered by the West Antarctic Ice Sheet, which some climatologists warn could collapse, raising sea levels by 10 feet (3 m) or more in a short time. The Antarctic Peninsula, Marie Byrd Land, and the area east and north of the Transantarctic Mountains are part of West Antarctica. The eastern part of Antarctica is a large Precambrian craton known as East Antarctica, with ages extending to at least 3 billion years. The rocks of the ancient craton, however, were reworked in younger mountain-building events, including an Early Paleozoic event during which East Antarctica was incorporated into Gondwana.

Most of western Antarctica was built up through the accretion of microplates that include the Ellsworth Mountains terrane, the Antarctic Peninsula, Marie Byrd Land, and an unnamed block of igneous and metamorphic rocks. Compared with the subdued (subglacial) topography of East Antarctica, western Antarctica has relatively rugged, mountainous topography.

The Transantarctic Mountains are up to 15,000 feet (4,570 m) high, and were formed during the Ross orogeny 500 million years ago. In contrast, the Ellsworth Mountains reach 16,000 feet (4,880 m) and were formed about 190 million years ago in the Early Mesozoic. The Antarctic Peninsula is the youngest addition to Antarctica, formed mostly in the Late Mesozoic to Early Cenozoic Andean orogeny (80–60 million years ago). Most activity in the Transantarctic Mountains was in the period of the breakup of Gondwana, as this region became a convergent margin continuous with the Andes of South America.

GEOLOGY, PALEONTOLOGY, AND PALEOCLIMATE

The Precambrian basement rocks of East Antarctica comprise the East Antarctic craton, with Archean cores surrounded by Proterozoic orogenic belts with younger deformation and metamorphism than the Archean blocks. These Archean cores include coastal areas of western Dronning Maud Land, Enderby Land, the Prince Charles Mountains, and the Vestfold Hills. The rocks in the Vestfold Hills include 2.5 billion-year-old gneisses derived from igneous rocks, and some indications of 2.8 billion-year-old gneisses in the area. The best known part of the East Antarctic craton is the Napier Complex in Enderby Land. This Archean granulite-gneiss belt includes 2.8 to 3.0 billion-year-old metamorphosed igneous gneisses, with some indication that initial igneous activity in the area may extend back to 3.8 billion years. Several deformation and metamorphic events are recorded at about 2.8 billion years ago, and a very high temperature metamorphic event recorded at 2.51–2.47 billion years ago. Additional deformation is recorded

Transantarctic Mountains (North Victoria Land) in Antarctica *(Hinrich Baesemann/dpa/Landov)* as East Antarctica became part of Gondwana, near the end of the Precambrian.

East Antarctica was part of Gondwana in the Early Paleozoic, resting in equatorial latitudes and accepting marine deposits of fossiliferous limestones from the tropical seas. These limestones are rich in trilobite and invertebrate fossils. West Antarctic was in the northern hemisphere in the Paleozoic, and not yet sutured with East Antarctica. By the Devonian, Gondwana, with East Antarctica, had drifted into southern latitudes and experienced a cooler climate, but still has a good fossil record of land plants in sandstone and siltstone beds exposed in the Ellsworth and Pensacola Mountains. The end of the Devonian (360 million years ago) witnessed a major glaciation as Gondwana became centered on the South Pole. Despite the glaciation, East Antarctica remained vegetated, and by the Permian many swamps across Antarctica were flourishing with the fernlike *Glossopteris* fauna, known throughout much of Gondwana. By the end of the Permian the climate over much of Gondwana had turned hot and dry.

The end-Permian warming caused the polar ice caps on Eastern Gondwana, including Antarctica, to melt, and the continent became a vast desert. Still, seed ferns and giant reptiles, including *Lystrosaurus,* inhabited the land, and thick beds of sandstone and shale were deposited on the East Antarctic platform. The Antarctic Peninsula was forming during the Jurassic (206–146 million years ago), and beech trees began to take over the floral assemblage. West Antarctica had accreted to the East Antarctic craton and was covered in conifer forests through the Cretaceous, gradually replaced by the beech trees toward the end of the period. The seas around Antarctica were inhabited by ammonites.

Modern-day Antarctica began to take shape in the Cenozoic. The Antarctic Peninsula and Western Antarctica are an extension of the Andes of South America.

CLIMATE AND ICE CAP

The climate of Antarctica is the coldest, driest, and windiest on Earth, with the lowest recorded temperature being -129°F (-89°C) from the Vostok weather station, located at two miles (three km) elevation in Antarctica. Despite being covered in ice, the climate of Antarctica is best described as a dry or polar desert, since the amount of precipitation is so low, with the South Pole receiving fewer than four inches (10 cm) of rainfall equivalent each year. Although it is covered in ice, interior Antarctica is technically the largest desert on Earth. Temperatures show a considerable range, from -112°F to -130°F (-90°C to -90°C) in interior winters, to 41°F to 59°F (5°C to 15°C) along the coastline in summer. In general, the eastern part of the continent is colder than the western part, because it has a higher elevation.

Ice calving from an ice front off Adelaide Island, Antarctica *(British Antarctic Survey/Photo Researchers, Inc.)*

Although 98 percent of Antarctica is covered in ice, a few places are ice-free. The Dry Valleys are the largest area on Antarctica not covered by ice. The Dry Valleys, located near McMurdo Sound on the side of the continent closest to New Zealand, have a cold desert climate and receive only four inches (10 cm) of precipitation per year, overwhelmingly in the form of snow. The Dry Valleys are one of the coldest, driest places on Earth and are used by researchers from the National Aeronautics and Space Administration (NASA) as an analog for conditions on Mars. No vegetation exists in the Dry Valleys, but a number of unusual microbes live in the frozen soils and form cyanobacterial mats in places. In the Southern Hemisphere summer, glaciers in the surrounding Transantarctic Mountains release significant quantities of meltwater so that streams and lakes form over the thick permafrost in the valleys.

The edge of the continent is often hit by strong katabatic winds, formed when high-density air forms over the ice cap, and then moves rapidly downhill, typically along glaciated valleys, at times reaching hurricane strength in force. High-density air often forms over the ice cap because the ice cools the air through radiative cooling effects, making it denser. This dense air then finds the lowest points to flow downhill, and because of the high elevation of central Antarctica the winds pick up enormous speed through gravitational energy, until they roar out of the coastal valleys as exceptionally cold channels of hurricane-force winds.

ANTARCTIC ICE CAP AND GLOBAL WARMING

The Antarctic ice cap is huge, containing more than 70 percent of the fresh water on the planet. It is about the same size as the Laurentide ice sheet that covered the northern part of North America in the last ice age. If the ice in the Antarctic ice cap all melted, sea levels would rise by 230 feet (70 m), yet there is no evidence that the south polar ice cap is melting, and it has been stable for about the past 5 million years. Many models predict that global warming may increase precipitation in Antarctica and actually cause the ice cap to increase in volume and lower sea levels by 0.04 inches (0.09 cm) per year.

The ice cap consists of a vast area of ice more than one mile (1.6 km) thick, covering nearly all of East Antarctica in Queen Maud Land and Wilkes Land. The geology of this region is understood through nunataks, isolated peaks piercing through the ice cap mostly near the coast, and in the Transantarctic Mountains. Likewise, most of West Antarctica is covered by ice, including Marie Byrd Land, Ellsworth Land, Palmer Land, and the Antarctic Peninsula. The large Ross Ice Shelf is located between Marie Byrd Land and the Transantarctic Mountains, while on the other side of the continent, the Ronne Ice Shelf fills the space between the Antarctic Peninsula and the Transantarctic Mountains.

Global warming is not significantly affecting most of Antarctica, since the interior of the continent is isolated from the global climate system. The ice cap in central Antarctica is presently growing in volume, whereas some of the peripheral ice shelves, such as along the northern parts of the Antarctic Peninsula, are losing volume. For instance, in 2003 parts of the Larsen ice shelf on the northern Antarctic Peninsula began collapsing from a combination of global warming and other cyclical processes. Farther south on the Peninsula, the Wilkins ice shelf lost 220 square miles (570 km^2) of ice in 2008, but it is still not well established whether these giant collapses result from global warming or whether similar processes have existed for many thousands of years. In support of the latter idea is the observation that the overall amount of sea ice around Antarctica has remained stable over the past 30 years, although there is considerable variation month to month and year to year.

See also CONVERGENT PLATE MARGIN PROCESSES; CRATON; GLACIER, GLACIAL SYSTEMS; GLOBAL WARMING; GONDWANA, GONDWANALAND.

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Arabian geology

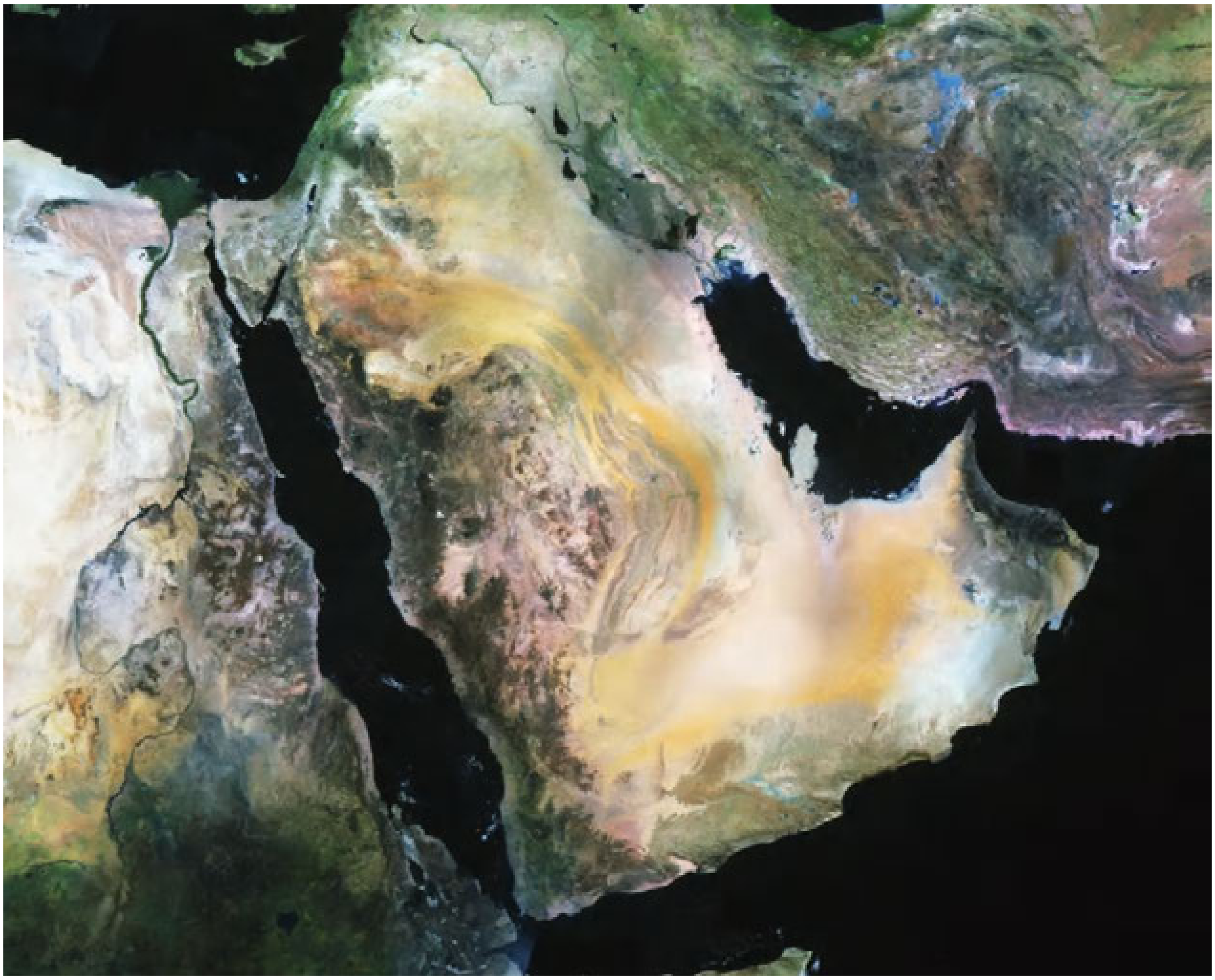
The Arabian Peninsula can be classified into two major geological provinces, including the Precambrian Arabian shield and the Phanerozoic cover. The Arabian shield comprises the core and deep-lying rocks of the Arabian Peninsula, a landmass of near trapezoidal shape bounded by three water bodies. The Red Sea bounds it from the west, the Arabian Sea and the Gulf of Aden from the south, and the Arabian Gulf and Gulf of Oman bound it on the east.

The Precambrian Shield is located along the western and central parts of the peninsula. It narrows in the north and the south but widens in the central part of the peninsula. The shield lies between latitudes 12° and 30° north and between longitudes 34° and 47° east. The Arabian shield is considered part of the Arabian-Nubian shield formed in the upper Proterozoic Era and stabilized in the Late Proterozoic around 600 million years ago. The shield has since subsided and been covered by thick deposits of Phanerozoic continental shelf sediments along the margins of the Tethys Ocean. Later in the Tertiary the Red Sea rift system rifted the Arabian-Nubian shield into two fragments.

Phanerozoic cover rocks unconformably overlie the eastern side of the Arabian shield, forming the Tuwaiq Mountains, and these rocks dip gently toward the east. Parts of the Phanerozoic cover are found overlying parts of the Precambrian shield, such as the Quaternary lava flows of Harrat Rahat in the middle and northern parts of the shield, as well as some sandstones, including the Saq, Siq, and Wajeed sandstones in different parts of the shield. The Phanerozoic rocks are well exposed again in tectonic uplifts in the Oman (Hajar) Mountains in the east, where the geology is well known.

TECTONIC MODELS OF THE ARABIAN SHIELD

The Arabian shield includes an assemblage of Middle to Late Proterozoic rocks exposed in the western and central parts of the Arabian Peninsula and overlapped to the north, east, and south by Phanerozoic sedimentary cover rocks. Several parts of the shield are covered by Tertiary and Quaternary lava flows that were extruded along with rifting of the Red Sea starting about 30 million years ago. Rocks of the Arabian shield may be divided into assemblages of Middle to Late Proterozoic stratotectonic units, volcanosedimentary, and associated mafic to intermediate intrusive rocks. These rocks are divided into two major categories, the layered rocks and the intrusive rocks. Researchers variously interpret these assemblages as a result of volcanism and magmatism in continental basins or above subduction zones. More recently workers suggested that many of these assemblages belong to Late Proterozoic volcanic-arc



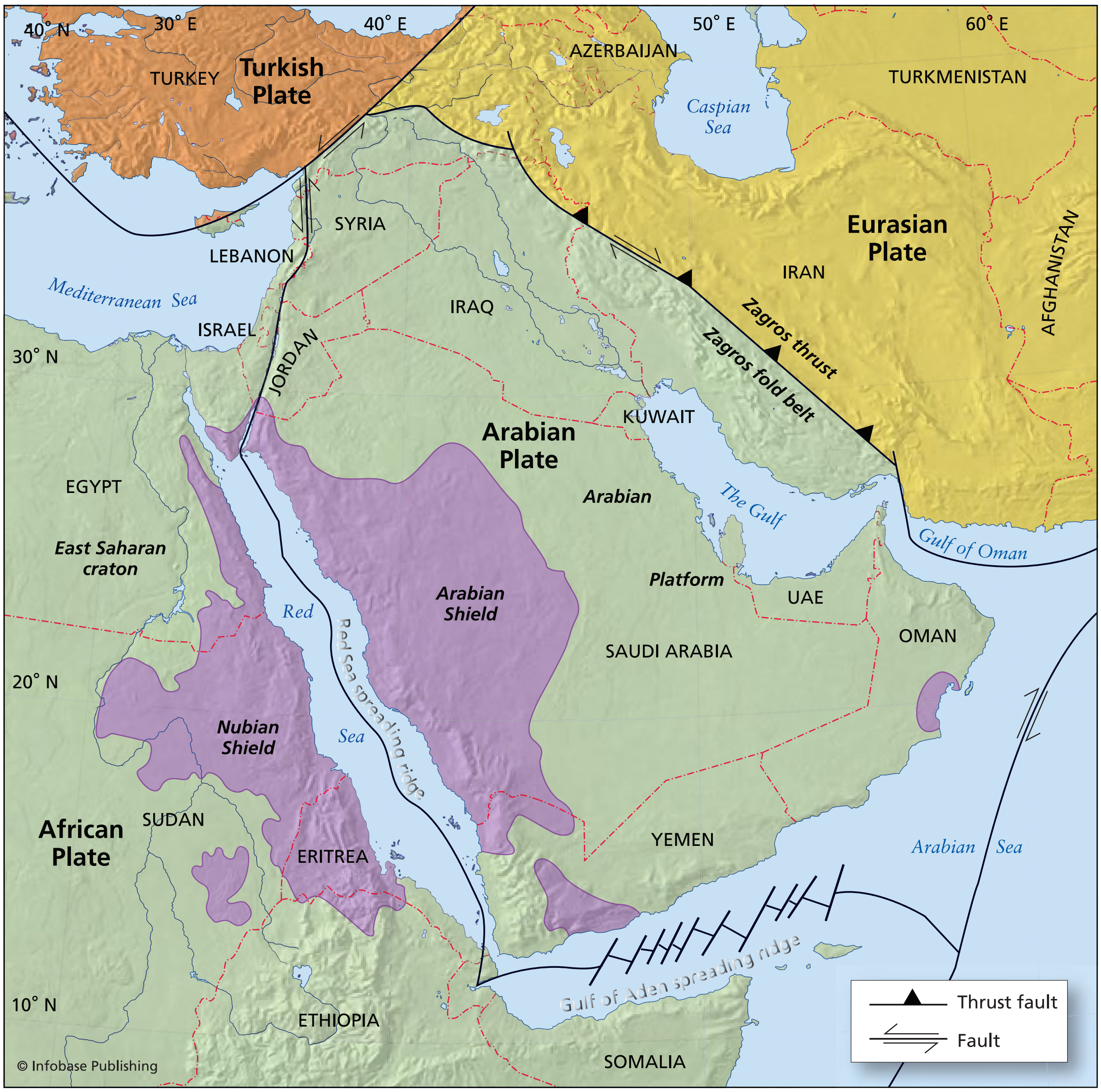
American Landsat image of Arabia. The Rub'a Khali (Empty Quarter) desert forms the great yellow sand sheet in the southern part of the peninsula, the Arabian shield forms the dark-colored terrane in the west, and the Semail ophiolite (oceanic crust and lithosphere) forms the dark area in the southeast. The fertile Mesopotamia area (in dark green, between the Tigris and Euphrates Rivers) separates Arabia from the Zagros Mountains of Iran. *(Earth Satellite Corporation/Photo Researchers, Inc.)*

systems that comprise distinct tectonic units or terranes, recognized following definitions established in the North America cordillera.

Efforts in suggesting models for the evolution of the Arabian shield started in the 1960s. Early workers suggested that the Arabian shield experienced three major orogenies in the Late Proterozoic Era. They also delineated four classes of plutonic rocks that evolved in chemistry from calc-alkaline to peralkaline through time. In the 1970s a great deal of research emerged concerning models of the tectonic evolution of the Arabian shield. Two major models emerged from this work, including mobilistic plate tectonic models and a nonmobilistic basement-tectonic model.

The main tenet of the plate tectonic model is that the evolution of the Arabian shield started and took place in an oceanic environment, with the formation of island arcs over subduction zones in a huge oceanic basin. On the contrary, the basement-tectonic model considers that the evolution of the Arabian shield started by the rifting of an older craton or continent to form intraoceanic basins that became the sites of island arc systems. In both models, late stages of the formation of the Arabian-Nubian shield are marked by the sweeping together and collision of the island arcs systems, thrusting of the ophiolites onto continents, and cratonization of the entire orogen, forming one craton attached to the African craton. Most subsequent investigators in the 1970s supported one of these two models and tried to gather evidence to support that model.

As more investigations, mapping, and research were carried out in the 1980s and 1990s, a third model invoking microplates and terrane accretion



Simple map showing the geology of the Arabian Peninsula

was suggested. This model suggests the existence of an Early to mid-Proterozoic (2.0–1.63 billion-year-old) craton that was extended, rifted, then dispersed, causing the development of basement fragments that were incorporated as allochthonous microplates into younger tectonostratigraphic units. The tectonostratigraphic units include volcanic complexes, ophiolite complexes, and marginal-basin and fore-arc stratotectonic units that accumulated in the intraoceanic to continental-marginal environments that resulted from rifting of the preexisting craton. These rocks, including the older continental fragments, constitute five large and five small tectonostratigraphic terranes accreted and swept together between 770 and 620 million years ago to form a neocraton on which younger volcanosedimentary and sedimentary rocks were deposited. Most models developed in the period since the early 1990s represent varieties of these three main classical models, along with a greater appreciation of the formation of the supercontinent of Gondwana in the formation of the Arabian-Nubian shield.

GEOLOGY OF THE ARABIAN SHIELD

Peter Johnson of the U.S. Geological Survey and his coworkers have synthesized the geology of the

Arabian shield and proposed a general classification of the geology of the Arabian shield that attempts to integrate and resolve the differences between the previous classifications. According to this classification, the layered rocks of the Arabian shield are divided into three main units separated by periods of regional tectonic activity (orogenies). This gives an overall view that the shield was created through three tectonic cycles. These tectonic cycles include early, middle, and late Upper Proterozoic tectonic cycles.

The early Upper Proterozoic tectonic cycle covers the period older than 800 million years and includes the oldest rock groups that formed before and up to the Aqiq orogeny in the south and up to the Tuluhah orogeny in the north. In this general classification the Aqiq and Tuluhah orogenies are considered part of one regional tectonic event, or orogeny, that is given a combined name of Aqiq-Tuluhah orogeny.

The middle Upper Proterozoic tectonic cycle is considered to have taken place between 700 and 800 Ma. It includes the Yafikh orogeny in the south and the Ragbah orogeny in the north. These two orogenies were combined into one regional orogeny, the Yafikh-Ragbah orogeny.

The late Upper Proterozoic tectonic cycle took place in the period between 700 and 650 Ma. It includes the Bishah orogeny in the south and the Rimmah orogeny in the north. These two orogenies are combined into one regional orogeny, the Bishah-Rimmah orogeny.

CLASSIFICATION OF ROCK UNITS

The layered rocks in the Arabian shield are classified into three major rock units, each of them belonging to one of the three tectonic cycles mentioned above. These major layered rock units are the lower, middle, and upper layered rock units.

The lower layered rock unit covers those rock groups that formed in the early upper Proterozoic tectonic cycle (older than 800 Ma) and includes rocks with continental affinity. The volcanic rocks that belong to this unit are characterized by tholeiitic basalt compositions and by the domination of basaltic rocks older than 800 Ma. The rock groups of this unit are located mostly in the southwestern and eastern parts of the shield.

The rock groups of the lower layered unit include rocks formed in an island arc environment and characterized by basic tholeiitic volcanic rocks (Baish and Bahah Groups) and calc-alkaline rocks (Jeddah Group). In some places these rocks overlie highly metamorphosed rocks of continental origin (Sabia Formation and Hali schists) considered to have been brought into the system either from a nearby craton such as the African craton, or from microplates rifted from the African plate such as the Afif microplate.

The middle layered rock unit includes the layered rock groups that formed during the middle upper Proterozoic tectonic cycle between 700 and 800 Ma ago. The volcanic rocks are predominately intermediate igneous rocks characterized by a calc-alkaline nature. These rocks are found in many parts of the shield with a greater concentration in the north and northwest, and scattered outcrops in the southern and central parts of the shield.

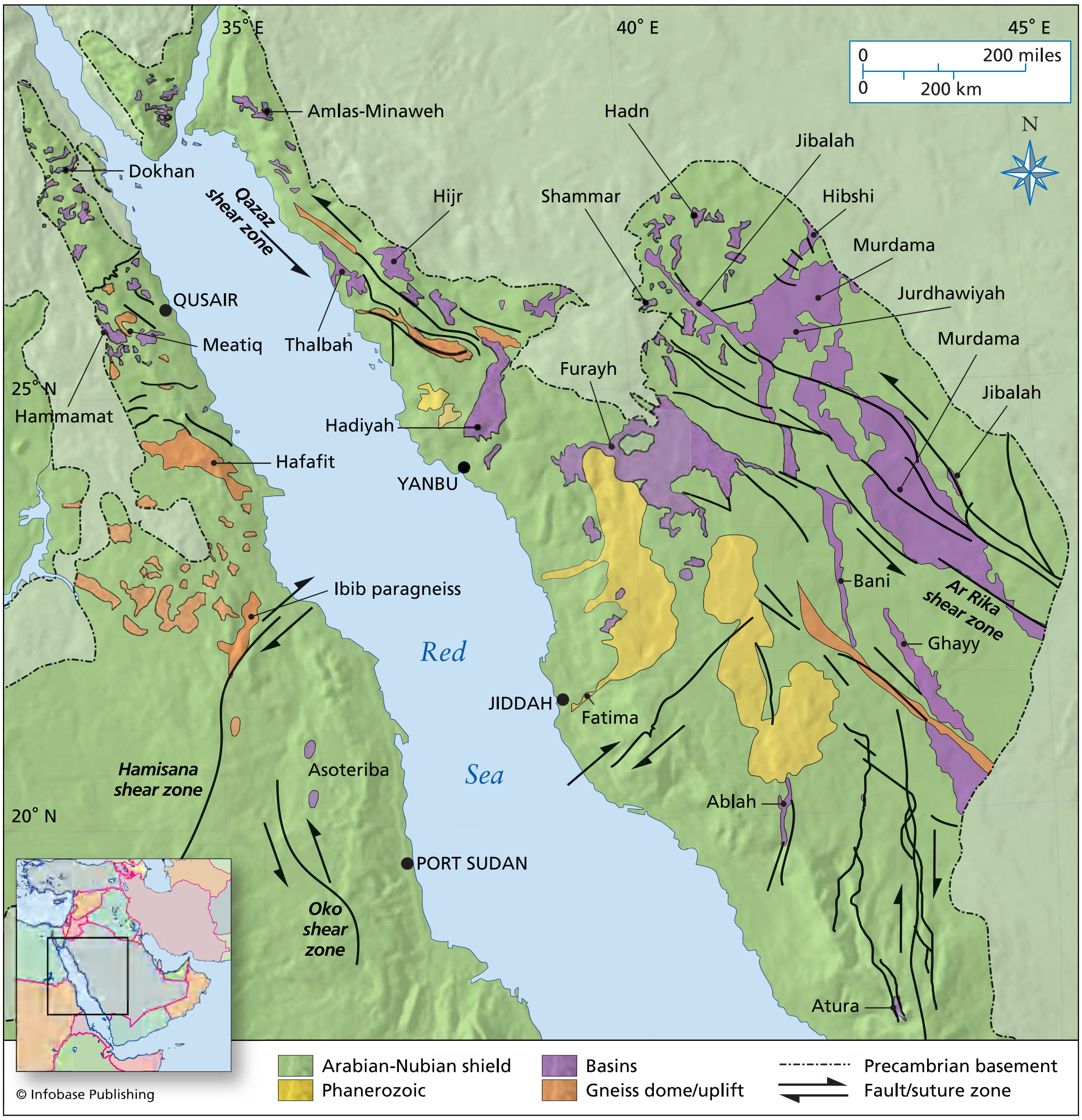
The upper-layered rock unit includes layered rock groups that formed in the late upper Proterozoic tectonic cycle in the period between 700 and 560 Ma ago and are predominately calc-alkaline, alkaline intermediate, and acidic rocks. These rock groups are found in the northeastern, central, and eastern parts of the shield.

INTRUSIVE ROCKS

Intrusive rocks that cut the Arabian shield are divided into three main groups, called (from oldest to youngest) Pre-orogenic, Syn-orogenic, and Post-orogenic.

The preorogenic intrusions cut through the lower-layered rocks unit only and not the other layered rock units. They are considered older than the middle-layered rock unit but younger than the lower-layered rock unit. These intrusions are characterized by their calcic to calc-alkaline composition. They are dominated by gabbro, diorite, quartz-diorite, trondhjemite, and tonalite. These intrusions are found in the southern, southeastern, and western parts of the shield and coincide with the areas of the lower-layered rocks unit. These intrusions are assigned ages between 700 and 1,000 million years. Geochemical signatures including strontium isotope ratios show that these intrusions were derived from magma that came from the upper mantle.

The synorogenic intrusions cut the lower and the layered rock units, as well as the preorogenic intrusions but do not cut or intrude the upper-layered rock units. These intrusions are considered older than the upper-layered rocks unit and younger than the preorogenic intrusions, as well as the lower- and the middle-layered rocks units, and they are assigned ages between 620 and 700 million years. Their chemical composition is closer to the granitic calc-alkaline to alkaline field than the preorogenic intrusions. These intrusions include granodiorite, adamalite, monzonite, granite, and alkali granite, with lesser amounts of gabbro and diorite in comparison with the preorogenic intrusions. The general form of these intrusions is batholithic bodies that cover wide areas. They are found mostly in the eastern, northern, and northeastern parts of the Arabian shield. The initial strontium ratio of these intrusions is higher than that



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Map showing the main tectonic terranes of the Arabian shield

of the preorogenic intrusions and indicates that these intrusions were derived from a magma generated in the lower crust.

Postorogenic intrusions cut through the three upper Proterozoic–layered rocks units as well as the pre- and synorogenic intrusions. These are assigned ages between 620 and 550 million years. They form circular, elliptical, and ringlike bodies that range in chemical composition from alkaline to peralkaline. These intrusions include peralkaline granites such as riebeckite granite, alkaline syenite, pink granite, biotite granite, monzogranite, and perthite-biotite granite.

Ringlike bodies and masses of gabbro are also common, and the postorogenic magmatic suite is bimodal in silica content. These intrusions are scattered in the Arabian shield, but they are more concentrated in the eastern, northern, and central parts of the shield. The initial strontium ratio of the postorogenic intrusions ranges between 0.704 and 0.7211, indicating that these intrusions were derived from a magma generated in the lower crust.

OPHIOLITE BELTS

Mafic and ultramafic rocks that comply with the definition of the ophiolite sequence are grouped into six major ophiolitic belts. Four of these belts strike north, while the other two strike east to northeast. These ophiolite belts include

- Amar-Idsas ophiolite belt
- Jabal Humayyan-Jabal Sabhah ophiolite belt
- Bijadiah-Halaban ophiolite belt
- Hulayfah-Hamdah "Nabitah" ophiolite belt
- Bir Umq-Jabal Thurwah ophiolite belt
- Jabal Wasq-Jabal Ess ophiolite belt

These rocks were among other mafic and ultramafic rocks considered as parts of ophiolite sequences, but later only these six belts were considered to comply with the definition of ophiolite sequences. However, the sheeted dike complex of the typical ophiolite sequence is not clear or absent in some of these belts, suggesting that the dikes may have been obscured by metamorphism, regional deformation, and alteration. These belts are considered to represent suture zones where convergence between plates or island arc systems took place, and are considered as the boundaries between different tectonic terranes in the shield.

NAJD FAULT SYSTEM

One of the most striking structural features of the Arabian shield is the existence of a fault system in a zone 185 miles (300 km) wide with a length of nearly 750 miles (1,200 km), extending from the southeastern to the northwestern parts of the shield. This system was generated just after the end of the Hijaz tectonic cycle, and it was active from 630 to 530 Ma, making it the last major event of the Precambrian in the Arabian shield. These faults are left-lateral strike-slip faults with a 150-mile (250 km) cumulative displacement on all faults in the system.

The main rock group formed during and after the existence of the Najd fault system is the Jibalah Group. This group formed in the grabens that were formed by the Najd fault system and are the youngest rock group of the Precambrian Arabian shield. The Jibalah Group formed between 600 and 570 Ma ago. The Jibalah Group is composed of coarse-grained clastic rocks and volcanic rocks in the lower parts, stromatolitic and cherty limestone and argillites in the middle parts, and fine-grained clastic rocks in the upper parts. These rocks were probably deposited in pull-apart basins that developed in extensional bends along the Najd fault system.

TECTONIC EVOLUTION OF THE ARABIAN SHIELD

The Arabian shield is divided into five major terranes and tectonostratigraphic units separated by four major suture zones, many with ophiolites along them. The five tectonic terranes include the Asir, Al-Hijaz, Midyan, Afif, and Ar-Rayn. The first three terranes are interpreted as interoceanic island arc terranes, while the Afif terrain is considered continental, and the Ar-Rayn terrain is considered to be probably continental. The four suture zones include the Bir Omq, Yanbu, Nabitah, and Al-Amar-Idsas belts. These suture zones represent the collision and suturing that took place between different tectonic terranes in the Arabian shield. For example, the Bir Omq belt represents the collision and suturing between two island arc terranes of Al-Hijaz and Asir, while the Yanbu suture zone represents the collision zone between the Midyan and Al-Hijaz island arc terranes. The Nabitah zone represents collision and suturing between a continental microplate (Afif) in the east and island arc terranes (Asir and Al-Hijaz) in the west; Al-Amar Idsas suture represents a collision and suturing zone between two continental microplates, Afif and Ar-Rayn.

Five main stages are recognized in the evolution of the Arabian shield, including rifting of the African craton (1,200–950 million years ago), formation of island arcs over oceanic crust (950–715 million years ago), formation of the Arabian shield craton from the convergence and collision of microplates with adjacent continents (715–640 million years ago), continental magmatic activity and tectonic deformation (640–550 million years ago), and epicontinental subsidence (550 million years ago).

Information about the rifting stage (1,200–950 million years ago) is limited, but the Mozambique belt in the African craton underwent rifting in the interval between 1,200 and 950 million years ago. This rifting formed an oceanic basin along the present northeastern side of the African craton. This was a part of the Mozambique Ocean that separated the facing margins of East and West Gondwana. Alternatively there may have been more than one ocean basin, separated by rifted microcontinental plates such as the Afif microcontinental plate.

The island arc formation stage (950–715 million years ago) is characterized by the formation of oceanic island arcs in the oceanic basins formed in the first stage. The stratigraphic records of volcanic and sedimentary rocks in the Asir, Al-Hijaz, and some parts of the Midyan terranes present rocks with ages between 900 and 800 million years. These rocks are of mafic or bimodal composition, and are considered products of early island arcs, particularly in the Asir terrain. These rocks show mixing or the involvement of rocks and fragments formed in the previous stage of rifting of the African craton.

The formation of island arc systems did not take place at the same time, but rather different arc systems evolved at different times. The Hijaz terrain is considered the oldest island arc, formed between 900 and 800 million years ago. This terrane may have encountered continental fragments now represented by the Khamis Mushayt Gneiss and Hali Schist, which are considered parts of, or derived from, the old continental crust from the previous stage of rifting.

Later on in this stage (760–715 million years ago) three island arc systems apparently formed simultaneously. These are the Hijaz, Tarib, and Taif island arc systems. These island arc systems evolved and formed three crustal plates, including the Asir, Hijaz, and Midyan plates. Later in this stage the Amar Andean arc formed between the Afif plate and Ar-Rayn plate, and it is considered part of the Ar-Rayn plate. Oceanic crustal plateaus may have been involved in the formation of the oceanic crustal plates in this stage.

In the collision stage (715–640 million years ago) the five major terranes that formed in the previous stages were swept together and collisions took place along the four suture zones mentioned above. The collision along these suture zones did not take place at the same time. For example, the collision along the Hijaz and Taif arcs occurred around 715 million years ago, and the collision along Bir Omq suture zone took place between 700 and 680 million years ago, while the island arc magmatic activity in the Midyan terrain continued until 600 million years ago. The collision along Nabitah suture zone was diachronous along strike. The collision started in the northern part of the Nabitah suture between Afif and the Hijaz terranes at about 680 to 670 million years ago, and at the same time the southern part of the suture zone was still experiencing subduction. Further collision along the Nabitah suture zone shut off the arc in the south, and the Afif terrain collided with the Asir terrain. As a result, the eastern Afif plate and the western island arc plates of the Hijaz and Asir were completely sutured along the Nabitah orogenic belt by 640 Ma. In this stage three major magmatic arcs developed, and later on in this stage they were shut off by further collision. These arcs include the Furaih magmatic arc that developed on the northern part of the Nabitah suture zone and on the southeastern part of the Hijaz plate, the Sodah arc that developed on the eastern part of the Afif plate, and an Andean-type arc on the eastern part of the Asir plate.

The Ar-Rayn collisional orogeny along the Amar suture was between the two continental plates of Afif and Ar-Rayn, and took longer than any other collisions in the shield (from 700 to 630 million years ago). Many investigators suggest that the Ar-Rayn terrain is part of a bigger continent, which extends under the eastern Phanerozoic cover and is exposed in Oman. This terrane may have collided with or into the Arabian shield from the east and was responsible for the development of the Najd left-lateral fault system.

By 640 million years ago the five major terranes had collided with each other, forming the four mentioned suture zones, and the Arabian shield was stabilized. Since then, the shield behaved as one lithospheric plate until the rifting of the Red Sea. Orogenic activity inside the Arabian shield, however, continued for a period of about 80 million years after collision, during which time the Najd fault system developed as the last tectonic event in the Arabian shield in the late Proterozoic Era.

After development of the Najd fault system, tectonic activity in the Arabian shield ended, and the Arabian-Nubian shield subsided and was peneplained, as evidenced by the existence of epicontinental Cambro-Ordovician sandstone covering many parts of the shield in the north and the south. The stratigraphic records of the Phanerozoic cover show that the Arabian shield has been tectonically stable with the exception of ophiolite obduction in Oman and collision along the margins of the plate during the closure of the Tethys Sea until rifting of the Red Sea in the Tertiary.

PHANEROZOIC COVER OF THE ARABIAN SHIELD: OMAN MOUNTAINS

The northern and eastern parts of the Arabian Peninsula are composed of a series of sandstone, limestone, siltstone, evaporates, and rare volcanic rocks deposited in the Paleozoic, Mesozoic, and Cenozoic. These rocks are known as the Arabian platform, the youngest rocks of which consist of unconsolidated sands, silts, gravels, and sabkha deposits such as those that cover much of Kuwait, the Gulf States, and upper layers on the Arabian platform.

The Phanerozoic rocks of the Arabian platform dip to the east very gently, and gradually increase in thickness from a few feet where they overlie the Precambrian Arabian shield in the east, to more than six miles (10 km) in thickness in Oman, eastern Saudi Arabia, and beneath Kuwait. Since some of the thickest sections of the Arabian platform are known from Oman, these rocks are described in detail using the exposures in the northern Oman (Hajar) Mountains as examples.

The Oman, or Hajar, Mountains in northern Oman and the United Arab Emirates are located on the northeastern margin of the Arabian plate, 60–120 miles (100–200 km) from the active deformation front in the Gulf of Oman between Arabia and the Makran accretionary wedge of Asia. They are made up of five major structural units ranging in age from Precambrian to Miocene. These include the pre-Permian basement, Hajar Unit, Hawasina nappes, Semail ophiolite and metamorphic sole, and postnappe structural units.

The Hajar Mountains reach up to 1.8 miles (three km) high, displaying many juvenile topographic features such as straight mountain fronts and deep, steep-walled canyons that may reflect active tectonism causing uplift of these mountains. The present height and ruggedness of the Hajar mountainous area is a product of Cretaceous ophiolite obduction, Tertiary extension, and rejuvenated uplift and erosion that was initiated at the end of the Oligocene and continues to the present. The Sayq Plateau southwest of Muscat is 1.2–1.8 miles (2–3 km) in elevation. Jabal Shams on the margin of the Sayq Plateau is the highest point in Arabia, rising more than 1.8 miles (3 km) in the central Hajar Mountains. The heights decrease gradually northward, reaching 1.2 miles (2 km) on the Musandam peninsula. There the mountain slopes drop directly into the sea.

Pre-Permian rocks are exposed mainly in the Jabal Akhdar, Saih Hatat, and Jabal J'Alain areas. The oldest structural unit includes a Late Proterozoic basement gneiss correlative with the Arabian-Nubian shield, overlain by a Late Proterozoic/Ordovician volcano-sedimentary sequence. The latter is divided into the Late Proterozoic/Cambrian Huqf Group and the Ordovician Haima Group. The Huqf Group is composed mainly of diamictites, siltstone, graywacke, dolostone, and intercalated mafic volcanics. The Ordovician Haima Group consists of a series of sandstones, siltstones, quartzites, skolithos-bearing sandstones, and shales, interpreted as subtidal to intertidal deposits.

The Hajar Unit represents the main part of the Permian/Cretaceous Arabian platform sequence that formed on the southern margin of the Neo-Tethys Ocean. These carbonates form most of the rugged peaks of Jabal Akhdar, form a rim around the southwestern parts of Saih Hatat, and continue in several thrust sheets in the Western Hajar region. They are well exposed on the Musandam peninsula. The Hajar Unit contains the Akhdar, Sahtan, Kahmmah, and Waisa Groups of mainly carbonate lithologies, overlain by the Muti Formation in the eastern Hajar, and the equivalent Ruus al Jibal, Elphinstone, Musandam, and Thamama Groups on the Musandam peninsula.

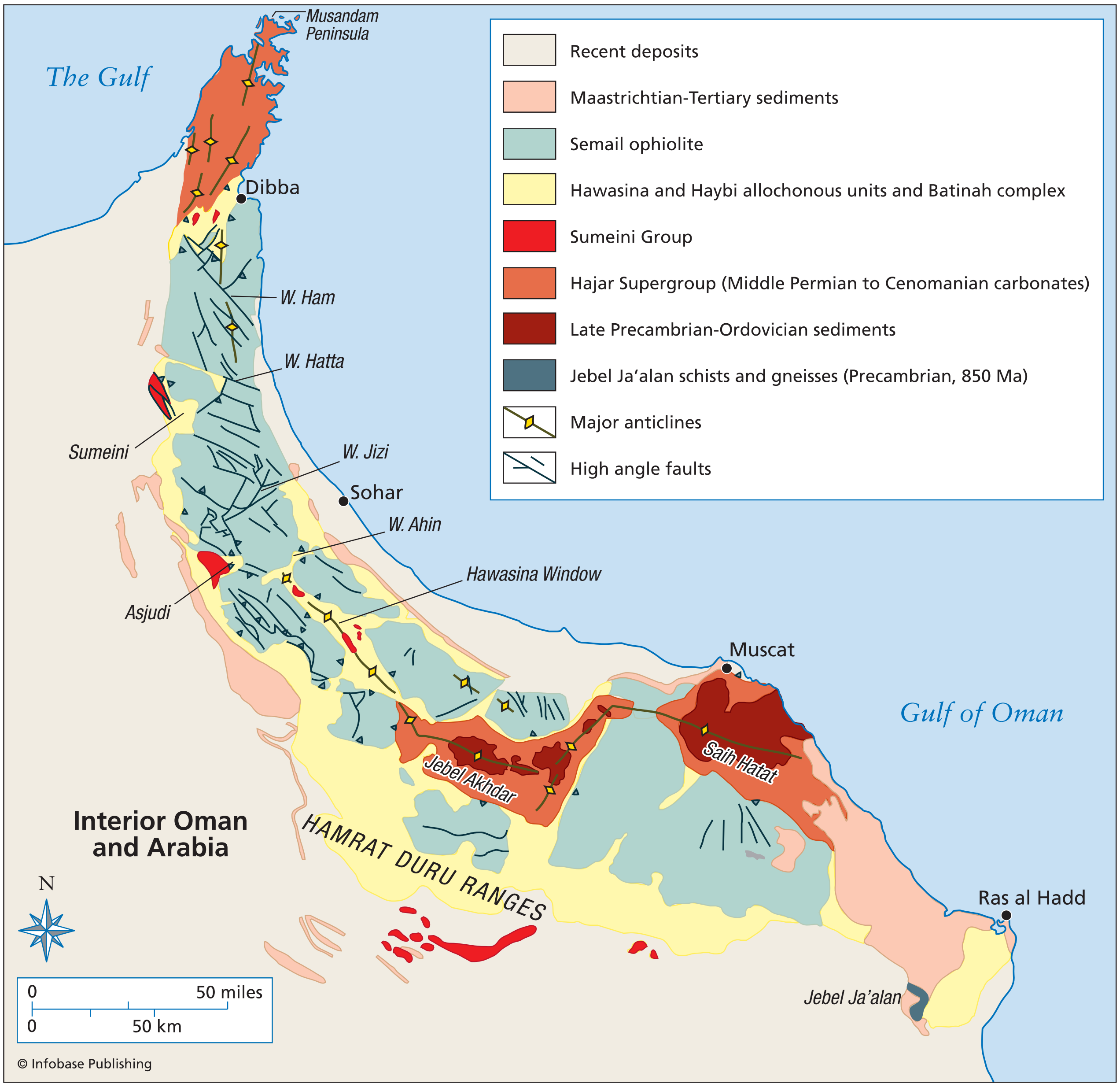
The Hawasina nappes consist of a series of Late Permian/Cretaceous sedimentary and volcanic rocks deposited in the Hawasina basin, between the Arabian continental margin and the open Neo-Tethys Ocean. The Hawasina nappes include the Hamrat Duru, Al Aridh, Kawr, and Umar Groups. Chaotic deposits of the Baid Formation are interpreted as a foundered carbonate platform. The Hamrat Duru Group includes radiolarian chert, gabbro, basaltic and andesitic pillow lava, carbonate breccia, shale, limestone, and sandstone turbidites. The Al Aridh Group contains an assemblage of basaltic andesite, hyaloclastite and pillow lavas, micrites, pelagic carbonates, carbonate breccias, chert, and turbidites. This is overlain by the Kawr Group, which includes basalts, andesites, and shallow marine carbonates. The Umar Group contains basaltic and andesitic pillow lavas, cherts, carbonate breccias, and micrites.

SEMAIL OPHIOLITE

The Semail nappe forms the largest ophiolitic sheet in the world, and it is divided into numerous blocks in the northern Oman Mountains. The Semail ophiolite contains a complete classic ophiolite stratigraphy, although parts of it are unusual in that it contains two magmatic sequences, including upper and lower units. The upper magmatic unit grades downward from radiolarian cherts and umber of the Suhaylah Formation, to basaltic and andesitic pillow lavas locally intruded by trondhjemites, through a sheeted diabase dike unit, and into massive and layered gabbros, and finally into cumulate gabbro, wehrlite, dunite, and clinopyroxenite. This upper magmatic sequence grades down from basaltic pillow lavas, into a sheeted dike complex, through isotropic then layered gabbros, then into cumulate gabbro and dunite. The Mohorovicic discontinuity is well exposed throughout the northern Oman Mountains, separating the crustal and the mantle sequences. The mantle sequence consists of tectonized harzburgite, dunite, and lherzolite, cut by pyroxenite dikes, and local chromite pods.

The metamorphic sole, or dynamothermal aureole, of the Semail ophiolite formed through metamorphism of rocks immediately under the basal thrust, heated and deformed during emplacement of the hot allochthonous sheets. In most places it consists of two units including a lower metasedimentary horizon, and an upper unit of banded amphibolites. The metamorphic grade increases upward through the unit to upper amphibolite facies near the contact with the Semail nappe.

Postnappe units consist of Late Cretaceous and Tertiary rocks. The Cretaceous Aruma Group consists of a lower unit of Turonian-Santonian polymict conglomerate, sandstone and shale of the Qahlah Formation, and an upper unit of Campanian-Maastrictian marly limestone and polymict breccia (Thaqab Formation). The Tertiary Hadhramaut



Geologic map of Oman. The world's largest ophiolite, the semail, is shown in green colors.

Group comprises Paleocene to Eocene limestones, marly limestone, dolostone, conglomerate, and sandstones that outcrop along the southern edge of the Batinah coastal plain at the border with the northeast flank of the Hajar Mountains.

QUATERNARY GEOLOGY OF NORTHERN ARABIA

Several levels of Quaternary fluvial terraces are preserved along the flanks of the Hajar Mountains in Oman. These can be divided in most places into an older lower-cemented terrace and an upper younger-uncemented terrace group. The lower-cemented terrace is one of the youngest geological units and has been used as a time marker to place constraints on the ages of structures. The terraces are younger than and unconformably overlie most faults and folds, but in several places faults and fracture intensification zones cut through the Quaternary terraces, providing some of the best evidence for the young age of some of the faults along the northeastern edge of the Arabian plate. These terraces grade both northward and southward into coalesced alluvial fans, forming bajada flanking the margins of the mountains. The northern alluvial plains grade into a narrow coastal plain along the Gulf of Oman.

The Oman (Hajar) Mountains are situated at the northeastern margin of the Arabian plate. This plate is bounded to the south and southwest by the active spreading axes of the Gulf of Aden and the Red Sea. On the east and west its border is marked by transcurrent fault zones of the Owen Fracture Zone and the Dead Sea Transform. The northern margin of the plate is marked by a complex continent-continent to continent-oceanic collision boundary along the Zagros and Makran fold and thrust belts.

Rocks of the Hajar Supergroup preserve a history of Permian through Cretaceous subsidence of the Arabian platform on the margin of the Neo-Tethys Ocean. Formations that now comprise the Hawasina nappes have biostratigraphic ages of 260–95 Ma, interpreted to have been deposited on the continental slope and in abyssal environments of the Neo-Tethys Ocean. By about 100 Ma ago, spreading in the Neo-Tethys generated the oceanic crust of the Semail ophiolite, which was detached in the oceanic realm and thrust over adjacent oceanic crust soon after its formation. Metamorphic ages for the initiation of thrusting range from 105 Ma to 89 Ma. The ophiolitic nappes moved toward the Arabian margin, forming the high-grade metamorphic sole during transport, and progressively scraping off layers of the Hawasina sediments and incorporating them as thrust nappes to the base of the ophiolite. The ophiolite reached the Arabian continental margin and was thrust over it before 85–75 Ma, as indicated by greenschist facies metamorphism in the metamorphic sole and by deformation of the Arabian margin sediments. Initial uplift of the dome-shaped basement cored antiforms of Jabel Akhdar and Saih Hatat may have been initiated during the late stages of the collision of the ophiolite with the Arabian passive margin, and may have been localized by preexisting basement horst and graben structures. The location and geometry of these massive uplifts is probably controlled by basement ramps. Uplift of these domes was pronounced during the Oligocene/Miocene, as shown by tilting of Late Cretaceous/Tertiary formations on the flanks of the domes. Uplift of the domes may have begun in the Oligocene, resulting from the propagation of a fault beneath the southern limbs of the folds. The uplift of the domes includes a complex history, involving several different events. Some uplift of the domes continues at present, whereas much of the Batinah coastal plain is subsiding.

In most of the Hajar Mountains, the Hawasina nappes structurally overlie the Hajar Supergroup, and form a belt of north or northeastward dipping thrust slices. On the southern margins of Jabal Akhdar, Saih Hatat, and other domes, however, the Hawasina form south-dipping thrust slices. Major valleys typically occupy the contact between the Hajar Supergroup and the Hawasina nappes, because of the many, easily erodable shale units within the Hawasina nappes. Several very large [~6 mile (10 km) scale] allochthonous limestone blocks known as the "Oman Exotics" are also incorporated into melange zones within the Hawasina nappes. These form light-colored, erosionally resistant cuestas, including Jabal Kawr and several smaller mountains south of Al Hamra.

South and southwest of the belt of ophiolite blocks, sediments of the Hamrat Duru Group are complexly folded and faulted in a regional foreland-fold-thrust belt and then grade into the Suneinah foreland basin. The Hamrat Duru rocks include radiolarian cherts, micritic limestones, turbiditic sandstones, shales, and calcarenite, all complexly folded and thrust faulted in an 18.5-mile (30-km)-wide fold/thrust belt.

A belt of regional anticlinal uplifts brings up carbonates of the Hajar Supergroup in the central part of the basin, as exposed at Jabal Salakh. These elongate anticlinal domes have gentle to moderate dips on their flanks, and are cut by several thrust faults that may be linked to a deeper system. This could be a blind thrust, or the folds could be flower structures developed over deep strike-slip faults. South of the Jabal Salakh fold belt, the surface is generally flat and covered by Miocene/Pliocene conglomerates of the Barzaman Formation, and cut by an extensive network of Quaternary channels of the active alluvial plain.

Tertiary/Quaternary uplift of the northern Oman Mountains may account for the juvenile topography of the area. One of the best pieces of evidence for young uplift of the Northern Oman Mountains comes from a series of uplifted Quaternary marine terraces, best exposed in the Tiwi area 31–62 miles (50–100 km) southeast of Muscat. The uplift is related to the contemporaneous collision between the northeastern margin of the Arabian plate and the Zagros fold belt and the Makran accretionary prism. The Hajar Mountains lie on the active forebulge of this collision, and the fault systems are similar to those found in other active and ancient forebulge environments. The amount of Quaternary uplift, estimated between 300 and 1,600 feet (100–500 m), is also similar to uplift in other forebulge environments developed on continental margins. This Quaternary uplift is superimposed on an older, Cretaceous/Tertiary (Oligocene) topography.

CENOZOIC GEOLOGY OF NORTHERN ARABIAN PLATE: KUWAIT

Kuwait is located in the northwest corner of the Arabian Gulf between 28°30′ and 30° north latitude, and 46°30′ to 48°30′ east longitude. It is approximately 10,700 square miles (17,818 km^2); the extreme north-south distance is 120 miles (200 km), the east-west distance is 100 miles (170 km).

To the south it shares a border with Saudi Arabia; to the west and north, it shares a border with Iraq. The semiarid climate of Kuwait is characterized by two seasons: a long, hot, humid summer, and a relatively cold, short winter. Summer temperatures range from 84.2 to 113°F (29–45°C), with relatively high humidity. The prevailing shamal winds from the northwest bring severe dust and sand storms from June to early August, with gusts up to 60 miles per hour (100 km/hr). Winter temperatures range from 46.4 to 64.4°F (8–18°C). Occasionally samum winds (meaning poison wind, describing the extremely hot and dry winds from the Sahara that can reach 130°F [55°C] bring more heat to people's bodies than can be removed by transpiration, and they lead to many cases of heatstroke. These winds come from the southwest during November. Annual precipitation averages 4.5 inches (11.4 mm) and rapidly infiltrates the sandy soil, leaving no surface water except in a few depressions. Most of the limited rainfall occurs in sudden squalls during the winter season.

Most of Kuwait is a flat, sandy desert. There is a gradual decrease in elevation from an extreme of 980 feet (300 m) in the southwest near Shigaya to sea level. The southeast is generally lower than the northwest. There are no mountains or rivers. The country can be divided into roughly two parts, including a hard, flat stone desert in the north with shallow depressions and low hills running northeast to southwest. The principal hills in the north are Jal al-Zor (475 feet or 145 m) and the Liyah ridge. Jal al-Zor runs parallel to the northern coast of Kuwait Bay for a distance of 35 miles (60 km). The southern region is a treeless plain covered by sand. The Ahmadi Hills (400 feet or 125 m) are the sole exception to the flat terrain. Along the western border with Iraq lies Wadi Al-Batin, one of the few valleys in Kuwait. The only other valley of note is Ash Shaqq, a portion of which lies within the southern reaches of the country. Small playas, or enclosed basins, are covered intermittently with water. During the rainy season they may be covered with dense vegetation; during the dry season they are often devoid of all vegetation. Most playas range between 650 and 985 feet (200–300 m) in length, with depths from 16 to 50 feet (5–15 m).

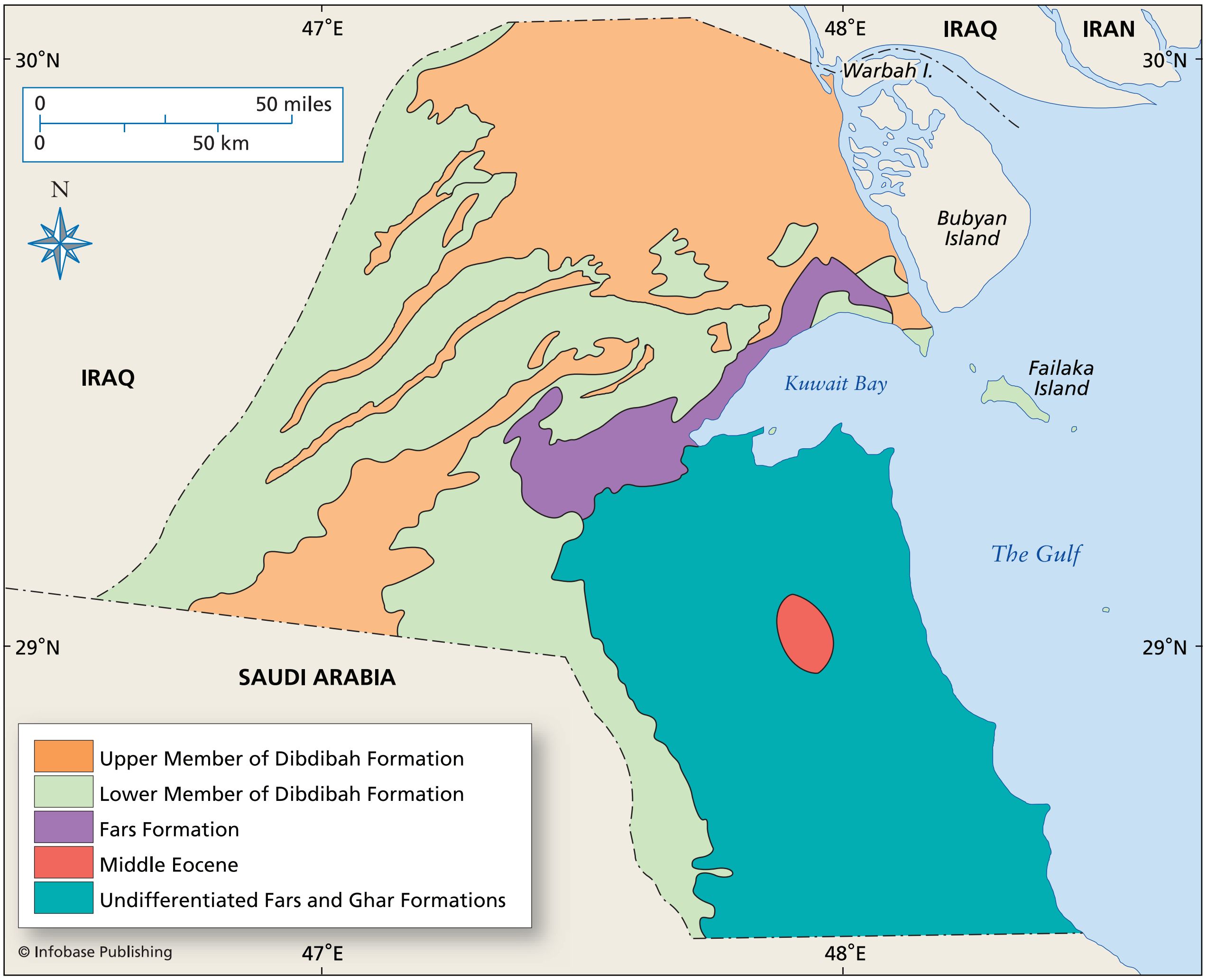
There are few sand dunes in Kuwait, occurring mainly near Umm Al-Neqqa and Al-Huwaimiliyah. The dunes at Umm Al-Neqqa are crescent-shaped barchan dunes with an average width of 550 feet (170 m) and average height of 25 feet (8 m). Those near Al-Huwaimiliyah are smaller, averaging 65 feet (20 m) wide and 7 feet (2 m) height, and are clustered into longitudinal dune belts. Both mobile and stable sand sheets occur in Kuwait. A major mobile sand belt crosses Kuwait in a northwest to southeast direction, following the prevailing wind pattern. Smaller sheets occur in the Al-Huwaimiliyah area, in the Al-Qashaniyah in the northeast, and in much of the southern region.

During the past few years overgrazing and an increase of motor vehicles in the desert have caused great destruction to the desert vegetation. Stabilized vegetated sheets have changed to mobile sheets as the protective vegetation is destroyed. The largest stabile sheet occurs at Shugat Al-Huwaimiliyah. Recently smaller sheets have begun to develop at Umm Al-Neqqa and Burgan oil field owing to an increase in desert vegetation resulting from a prohibition of traffic.

Kuwait Bay is a 25-mile (40-km) long indentation of marshes and lagoons. The coast is mostly sand interspersed with sabkhas and gravel. Sabkhas are flat, coastal areas of clay, silt, and sand often encrusted with salt. The northern portion of the bay is very shallow, averaging fewer than 15 feet (5 m). This part of the shore consists mostly of mud flats and sandy beaches. The more southern portion is relatively deep, with a bed of sand and silicic deposits. Most of the ports are situated in the southern area.

Kuwaiti territory includes 10 islands. Most are covered by scrub and a few serve as breeding grounds for birds. Bubiyan, the largest island, measuring approximately 600 square miles (1,000 km^2), is a low, level bare piece of land with mud flats along much of its north and west coasts that are covered during high tides. It is connected to the mainland by a concrete causeway. To its north lies Warba, another low-lying island covered with rough grass and reeds. East of Kuwait Bay and on the mud flats extending from Bubiyan lie three islands: Failaka, Miskan, and Doha. Failaka is the only inhabited island belonging to Kuwait. A small village, located near an ancient shrine, is set on a 30-foot (9-m) hill at the northwest point of the island. The rest of the island is flat with little vegetation. There are a few trees in the center of the island, and date trees are grown in the village. West of Kuwait City in the bay are two islets: Al-Qurain and Umm Al-Naml. On the south side of the gulf lie three more small islands: Qaruh, Kubbar, and Umm Al-Maradim. The last two are surrounded by reefs on three sides.

Kuwait occupies one of the most petroleum-rich areas in world, situated in a structurally simple region on the Arabian platform in the actively subsiding foreland of the Zagros Mountains to the north and east. Principal structural features of Kuwait include two subsurface arches (Kuwait arch and Dibdibba arch) and the fault-bounded Wadi Al-Batin. Faults defining Wadi Al-Batin are related to Tertiary extension in the region. The Kuwait and Dibdibba arches have no geomorphic expression, whereas the younger Bahra anticline and Ahmadi ridge have a surface expression and are structurally superimposed on the



Geologic map of Kuwait

Kuwait arch. Major hydrocarbon accumulations are associated with the Kuwait arch. The subsurface stratigraphy of Kuwait includes a nearly continuous section of Arabian platform sediments ranging in age from Cambrian through Holocene, although the pre-Permian rocks are poorly known. The Permian through Miocene section is 3.5–4 miles (6–7 km) thick in Kuwait but thickens toward the northeast. These rocks include continental and shallow marine carbonates, evaporites, sandstones, siltstones, and shales, with less common gravels and cherts. Plio-Pleistocene sand and gravel deposits of the Dibdibba Formation outcrop in northwestern Kuwait, and Miocene sands, clay, and nodular limestone of the Fars and Ghar Formation outcrop in the southeast. A small area of Eocene limestone and chert (Dammam Formation) outcrops south of Kuwait City on the Ahmadi Ridge.

The structural arches in Kuwait are part of a regional set of north-trending arches known as the Arabian folds, along which many of the most important oil fields in the Arabian Gulf are located. These arches are at least mid-Cretaceous. The orientation of the Arabian folds has been interpreted to be inherited from older structures in the Precambrian basement, with possible amplification from salt diapirism. The north-south trends may continue northward beneath the Mesopotamian basin and the Zagros fold belt.

The northwest trending anticlinal structures of the Ahmadi ridge and Bahra anticline are younger than the Arabian folds, and related to the Zagros collision, initiated in post-Eocene times. These younger folds seem to have a second-order control on the distribution of hydrocarbon reservoirs in Kuwait, as oil wells (and after the First Gulf War in 1990, oil lakes) are concentrated in northwest trending belts across the north-striking Kuwait arch. The Kuwait arch has a maximum structural relief in the region between Burgan and Bahra, with closed structural contours around the Wafra, Burgan, Magwa, and Bahra areas, and a partial closure indicating a domal structure beneath Kuwait City and Kuwait Bay. The superposition of the Kuwait arch and the shallow anticlinal structure of the Ahmadi ridge forms a total structural relief of at least one mile (1.6 km).

The northwest-trending Dibdibba arch represents another subsurface anticline in western Kuwait. The ridge is approximately 45 miles (75 km) long, and is an isolated domal structure, but has not to date yielded any significant hydrocarbon reservoirs.

Wadi Al-Batin is a large valley, 4–6 miles (7–10 km) wide, with relief of up to 185 feet (57 m). In the upper valley of the wadi, the valley sides are steep, but in southwestern Kuwait few ravines have steep walls taller than 15 feet (5 m). The wadi has a length of more than 45 miles (75 km) in Kuwait, and extends 420 miles (700 km) southwestward into Saudi Arabia, where it is referred to as Wadi Ar-Rimah. The ephemeral drainage in the wadi drains from the southwest, and has transported Quaternary and Tertiary gravels consisting of igneous and metamorphic rock fragments from the Saudi Arabian and Syrian deserts during Pleistocene pluvial episodes. The wadi widens toward the northeast and becomes indistinguishable from its surroundings northwest of Kuwait City. Ridges made of Dibdibba gravel define paleodrainage patterns of a delta system draining Wadi Al-Batin, and many of these gravel ridges stand out as prominent lineaments. Some of these gravel ridges are marked by faults on at least one side, suggesting a structural control on the drainage pattern.

Numerous small and several relatively large faults are revealed on seismic reflection lines across the wadi, and hydrological pumping tests show a break in the drawdown slope at the faults. The steep Miocene–late Eocene faults parallel to the wadi have displaced the block in the center of the wadi upward by 15–20 feet (25–35 m) relative to the strata outside the wadi, and those displacements die out toward the northeast.

See also CONVERGENT PLATE MARGIN PROCESSES; DESERTS; GONDWANA, GONDWANALAND; OPHIOLITES; PALEOZOIC; PETROLEUM GEOLOGY; PHANEROZOIC; PROTEROZOIC.

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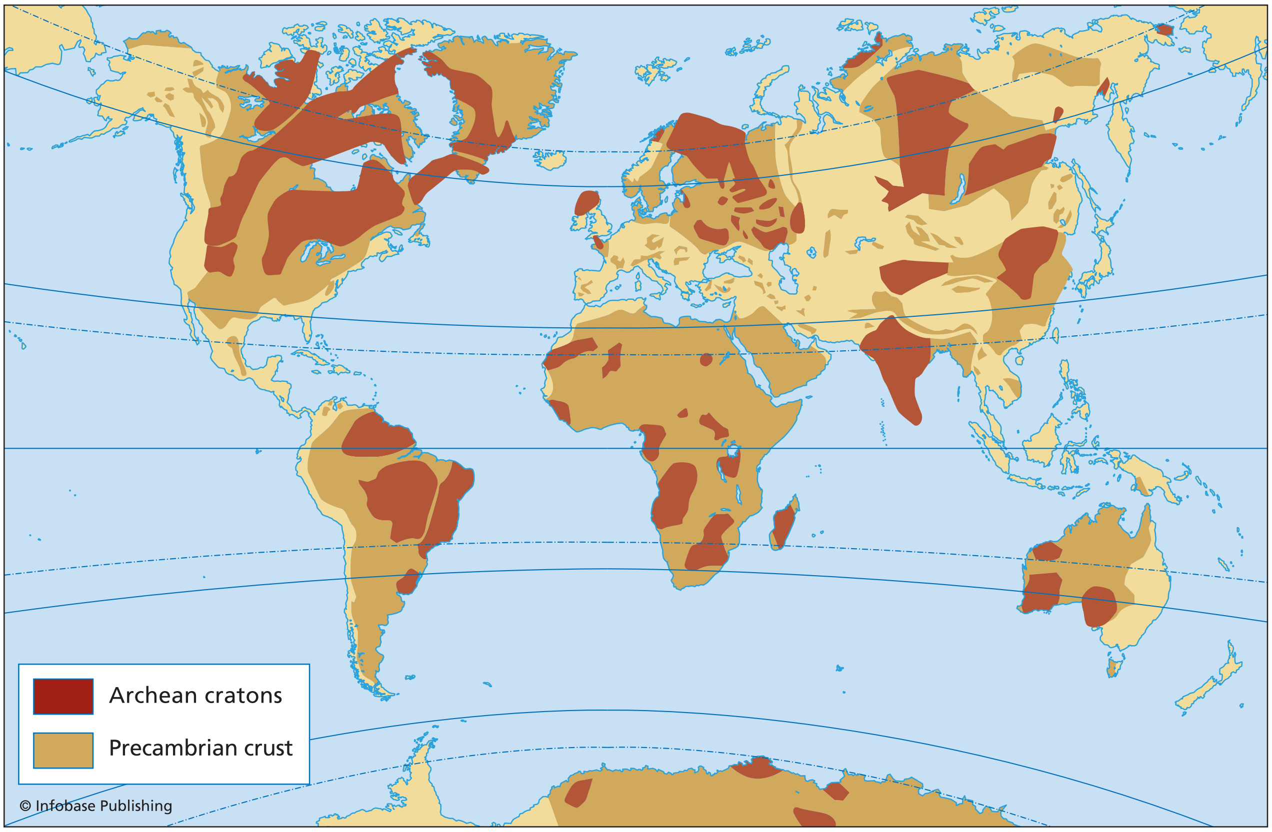
Archean **(Archaean)** Earth's first geological eon for which there is an extensive rock record, the Archean also preserves evidence for early primitive life-forms. The Archean is second of the four major eons of geological time: the Hadean, Archean, Proterozoic, and Phanerozoic. Some time classification schemes use an alternative division of early time, in which the Hadean, Earth's earliest eon, is considered the earliest part of the Archean. The Archean encompasses the one and one-half billion-year-long (Ga = giga année, or 10^9 years) time interval from the end of the Hadean eon to the beginning of the Proterozoic eon. In most classification schemes it is divided into three parts called eras, including the Early Archean (4.0–3.5 Ga), the Middle Archean (3.5–3.1 Ga), and the Late Archean, ranging up to 2.5 billion years ago.

Gneisses are strongly deformed rocks with a strong layering formed by the parallel alignment of deformed and flat minerals. The oldest known rocks on Earth are the 4.0 billion-year-old Acasta gneisses from northern Canada that span the Hadean-Archean boundary. Single zircon crystals from the Jack Hills and Mount Narryer in western Australia have been dated to be as old as 4.1–4.3 billion years. The oldest well-documented and extensive sequence of rocks on Earth is the Isua belt, located in western Greenland, estimated to be 3.8 billion years old. Life on Earth originated during the Archean, with the oldest known fossils coming from the 3.5 billion-year-old Apex chert in western Australia, and possible older traces of life found in the 3.8 billion-year-old rocks from Greenland.

Archean and reworked Archean rocks form more than 50 percent of the continental crust and are present on every continent. Most Archean rocks are found in cratons or as tectonic blocks in younger orogenic belts. Cratons are low-relief, tectonically stable parts of the continental crust that form the nuclei of many continents. Shields are the exposed parts of cratons, other parts of which may be covered by younger platformal sedimentary sequences. Archean rocks in cratons and shields are generally divisible into a few basic types. Relatively low-metamorphic-grade greenstone belts consist of deformed metavolcanic and metasedimentary rocks. Most Archean plutonic rocks are quartz and feldspar–dominated tonalites, trondhjemites, granodiorites, and granites that intrude or are in structural contact with strongly deformed and metamorphosed sedimentary and volcanic rocks in greenstone belt associations. Together these rocks form the granitoid-greenstone association that characterizes many Archean cratons. Granite-greenstone terranes are common in parts of the Canadian shield, South America, South Africa, and Australia. Low-grade cratonic basins are preserved in some places, including southern Africa and parts of Canada. High-grade metamorphic belts are also common in Archean cratons, and these generally include granitic, metasedimentary, and metavolcanic gneisses that were deformed and metamorphosed at middle to deeper crustal levels. Some well-studied Archean high-grade gneiss terranes include the Lewisian and North Atlantic Province, the Limpopo belt of southern Africa, the Hengshan of north China, and parts of southern India.

The Archean witnessed some of the most dramatic changes in Earth in the history of the planet. During the Hadean, the planet experienced frequent impacts of asteroids, some of which were large enough to melt parts of the outer layers of Earth and vaporize the atmosphere and oceans. Any attempts by life to get a foothold on the planet in the Hadean would have been difficult, and if any organisms were to survive this early bombardment, they would have to have been sheltered in some way from these dra-



Map of the world showing the distribution of Archean cratons, Precambrian crust, and Phanerozoic rocks (beige) *(modified from Timothy Kusky and Ali Polat)*

matic changes. Early atmospheres of Earth were blown away by asteroid and comet impacts, and by strong solar winds from an early T-Tauri phase of the Sun's evolution. Free oxygen was either not present or present in much lower concentrations, and the atmosphere evolved slowly to a more oxygenic condition.

Earth was also producing and losing more heat during the Archean than in more recent times, and the patterns, styles, and rates of mantle convection and the surface style of plate tectonics must have reflected these early conditions. Heat was still left over from early accretion, core formation, late impacts, and decay of some short-lived radioactive isotopes such as iodine 129. In addition, the main heat-producing radioactive decay series were generating more heat then than now, since more of these elements were present in older half-lives. In particular uranium 235, uranium 238, thorium 232, and potassium 40 were cumulatively producing two to three times as much heat in the Archean as at present. Since scientists know from the presence of rocks that formed in the Archean that the planet was not molten then, this heat must have been lost by convection of the mantle. It is possible that the temperatures and geothermal gradients were 10–25 percent hotter in the mantle during the Archean, but most of the extra heat was likely lost by more rapid convection and by the formation and cooling of oceanic lithosphere in greater volumes. The formation and cooling of oceanic lithosphere is presently the most efficient mechanism of global heat loss through the crust, and this mechanism was even more efficient in times of higher heat production. A highly probable scenario for removing the additional heat is that more ridges were present, producing thicker piles of lava, and moving at faster rates in the Archean compared to the present. There is currently much debate and uncertainty about the partitioning of heat loss among these mechanisms, and it is also possible that changes in mantle viscosity and plate buoyancy would have led to slower plate movements in the Archean as compared with the present.

GRANITE-GREENSTONE TERRANES

Archean granitoid-greenstone terrains are one of the most distinctive components of Archean cratons. About 70–80 percent of the Archean crust consists of granitoid material, most of which are compositionally tonalites and granodiorites (comprised of the minerals quartz, feldspar, and biotite). Many of these are intrusive into metamorphosed and deformed volcanic and sedimentary rocks in greenstone belts. Greenstone belts are generally strongly deformed and metamorphosed, linear to irregularly shaped assemblages of volcanic and sedimentary rocks. They derive their name from the green-colored metamorphic minerals chlorite and amphibole, reflecting the typical greenschist to amphibolite facies metamorphism of these belts. Early 19th century South African workers preferred to use the name schist belt for this assemblage of rocks, in reference to the generally highly deformed nature of the rocks. Volcanic rocks in greenstone belts most typically include basalts flows, many of which show pillow structures where they are not too intensely deformed, and lesser amounts of ultramafic, intermediate, and felsic rocks. Ultramafic volcanic rocks with quench-textures and high magnesium oxide (MgO) contents, known as komatiites, are much more abundant in

Satellite image of the Pilbara craton in northwestern Australia, showing prominent light-colored igneous batholiths that intruded darker colored greenstone belts consisting of metamorphosed and strongly deformed volcanic and sedimentary rocks *(Nick Short)*

Archean greenstone belts than in younger orogenic belts, but they are generally only a minor component of greenstone belts. Some literature leads readers to believe that Archean greenstone belts are dominated by abundant komatiites; however, this is not true. There have been an inordinate number of studies of komatiites in greenstone belts since they are such an unusual and important rock type, but the number of studies does not relate to the abundance of the rock type. Sedimentary rocks in greenstone belts are predominantly greywacke-shale sequences (or their metamorphic equivalents), although conglomerates, carbonates, cherts, sandstones, and other sedimentary rocks are found in these belts as well.

Suites of granitoid rock now deformed and metamorphosed to granitic gneisses typically intrude the volcanic and sedimentary rocks of the greenstone belts. The deformation of the belts has in many cases obscured the original relationships between many greenstone belts and gneiss terrains. Most of the granitoid rocks appear to intrude the greenstones, but in some belts older groups of granitic gneisses have been identified. In these cases it has been important to determine the original contact relationships between granitic gneisses and greenstone belts, as this relates to the very uncertain tectonic setting of the Archean greenstones. If contact relationships show that the greenstone belts were deposited unconformably over the granitoid gneisses, then it can be supposed that greenstone belts represent a kind of continental tectonic environment unique to the Archean. In contrast, if contact relationships show that the greenstone belts were faulted against or thrust over the granitoid gneisses, then the greenstone belts may be allochthonous (far-traveled) and represent closed ocean basins, island arcs, and other exotic terrains similar to orogenic belts of younger ages.

Before the mid 1980s and 1990s, many geologists believed that many if not most greenstone belts were deposited unconformably over the granitoid gneisses, based on a few well-preserved examples at places including Belingwe, Zimbabwe; Point Lake, Yellowknife, Cameron River, and Steep Rock Lake, Canada; and in the Yilgarn of western Australia. However, more recent mapping and structural work on these contact relationships have revealed that all of them have large-scale thrust fault contacts between the main greenstone belt assemblages and the granitoid gneisses, and these belts have since been reinterpreted as allochthonous oceanic and island arc deposits similar to those of younger mountain belts.

The style of Archean greenstone belts varies in an age-dependent manner. Belts older than 3.5 billion years have sediments including chert, banded iron formation, evaporites, and stromatolitic carbonates, indicating shallow-water deposition, and contain only very rare conglomerates. They also have more abundant komatiites than younger greenstone belts. Younger greenstone belts seem to contain more intermediate volcanic rocks such as andesites, and have more deep-water sediments and conglomerates. They also contain banded iron formations, stromatolitic carbonates, and chert. Since so few early Archean greenstone belts are preserved, it is difficult to know whether these apparent temporal variations represent real-time differences in the style of global tectonics or are a preservational artifact.

GRANULITE-GNEISS BELTS

High-grade granitoid gneiss terrains form the second main type of Archean terrain. Examples include the Limpopo belt of southern Africa, the Lewisian of the North Atlantic Province, the Hengshan of north China, and some less-well-documented belts in Siberia and Antarctica. The high-grade gneiss assemblage seems similar in many ways to the lower-grade greenstone belts, but more strongly deformed and metamorphosed, reflecting burial to 12.5–25 miles (20–40 km) depth. Strongly deformed mylonitic gneisses and partially melted rocks known as migmatites are common, reflecting the high degrees of deformation and metamorphism. Most of the rocks in the high-grade gneiss terranes are metamorphosed sedimentary rocks, including sandstones, greywackes, carbonates, as well as layers of volcanic rocks. Many are thought to be strongly deformed continental margin sequences with greenstone-type assemblages thrust over them, deformed during continent-continent collisions. Most high-grade gneiss terrains have been intruded by several generations of mafic dikes, reflecting crustal extension. These are typically deformed into boudins (thin layers in the gneiss), making them difficult to recognize. Some high-grade gneiss terrains also have large layered mafic/ultramafic intrusions, some of which are related to the mafic dike swarms.

The strong deformation and metamorphism in the Archean high-grade gneiss terranes indicates that they have been in continental crust that has been thickened to double crustal thicknesses of about 50 miles (80 km), and some even more. This scale of crustal thickening is typically associated with continental collisions and/or thickened plateaus related to Andean-style magmatism. High-grade gneiss terrains are therefore typically thought to represent continent-continent collision zones.

CRATONIC BASIN ASSOCIATION

A third style of rock association also typifies the Archean but is less common than the previous two associations. The cratonic basin association is characterized by little-deformed and -metamorphosed sequences of clastic and carbonate sedimentary rocks, with a few intercalated volcanic horizons. This category of Archean sequence is best developed on South Africa's Kaapvaal craton, and includes the Pongola, Witwatersrand, Ventersdorp, and Transvaal Supergroups. These groups include sequences of quartzites, sandstones, arkoses, carbonates, and volcanic rocks, deposited in shallow marine to lacustrine basins. They are interpreted to represent rift, foreland basin, and shallow marine cratonic eperic sea-type deposits, fortuitously preserved although only slightly metamorphosed and deformed. Several shallow-water carbonate shelf associations are also preserved, including the 3.0-Ga Steep Rock platform in Canada's Superior Province, and possibly also the 2.5-Ga Hamersley Group in western Australia.

EARLY LIFE

Life clearly had already established itself on Earth by the Early Archean. The geologic setting and origin of life are topics of intense current interest, research, and thought by scientists and theologians. Any models for the origin of life need to explain some observations about early life from Archean rock sequences.

Evidence for early life comes from two separate lines. The first includes remains of organic compounds and chemical signatures of early life, and the other line consists of fossils, microfossils, and microstructures. The best organic evidence for early life comes from kerogens, which are nonsoluble organic compounds or the nonextractable remains of early life that formed at the same time as the sediments in which they are found. Other extractable organic compounds such as amino acids and sugars may also represent remains of early life, but they are soluble in water and may have entered the rocks after the deposition of the sediments. Therefore most work on the biochemistry of early life has focused on the nonextractable kerogens. Biological activity changes the ratio of some isotopes, most notably carbon 13/carbon 12, producing a distinctive biomarker that is similar in Archean through present-day life. Such chemical evidence of early life has been documented in Earth's oldest sedimentary rocks, the 3.8-Ga Isua belt in Greenland.

The earliest known fossils come from the 3.5–3.6-Ga Apex chert of the Pilbara craton in western Australia. Three distinctive types of microfossils have been documented from the Apex chert. These include spheroidal bodies, 5–20 microns (one micron = 10^{-6} m) in diameter, some of which have been preserved in the apparent act of cell division. These microfossils are similar to some modern cyanobacteria, and show most clearly that unicellular life existed on Earth by 3.5 Ga. Simple rod-shaped microfossils up to one micron long are also present in the Apex chert, and their shapes and characteristics are also remarkably similar to modern bacteria. Less distinctive filamentous structures up to several microns long may also be microfossils, but they are less convincing than the spheroidal and rod-shaped bodies. All of these show, however, that simple, single-celled, probably prokaryotic life-forms were present on Earth by 3.5 billion years ago, 1 billion years after Earth formed.

Stromatolites are a group of generally dome-shaped or conical mounds, or sheets of finely laminated sediments produced by organic activity. They were most likely produced by cyanobacteria (formerly called blue-green algae) that alternately trapped sediment with filaments that protruded above the sediment/water interface and secreted a carbonate layer during times when little sediment was passing to be trapped. Stromatolites produced a distinctive layering by preserving this alternation between sediment trapping and secretion of carbonate layers. Common in the Archean and Proterozoic record, stromatolites show that life was thriving in many places in shallow water and was not restricted to a few isolated locations. The oldest stromatolites known are in 3.6 billion-year-old sediments from the Pilbara craton of western Australia, with many examples in early, middle, and late Archean rock sequences. Stromatolites seem to have peaked in abundance in the Middle Proterozoic, and largely disappeared in the Late Proterozoic with the appearance of grazing metazoans.

See also ATMOSPHERE; CRATON; ORIGIN AND EVOLUTION OF THE EARTH AND SOLAR SYSTEM; PHANEROZOIC; PRECAMBRIAN; PROTEROZOIC.

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Asian geology Asia is one of the most geologically and geomorphologically diverse continents on Earth, stretching from the Arctic to tropical regions, and from the world's highest peaks to broad plains, deserts, steeps, and deep basins. The range in age of features in Asia spans most of geological time, from 3.8 to 3.5 billion-year-old gneiss in China, to active volcanoes and sedimentary deposits across Asia. The India-Asia collision has resulted in Asia's being the most tectonically active region of continental crust in the world.

CHINA

China contains some of the most complex geology in the world, ranging from a number of ancient Archean cratons, to active tectonic belts, and offshore marine basins. The geomorphology changes from deep marine basins, to coastal plains, flat steppes, deserts, mountains, and the highest plateau of uplifted crust in the world. With such diversity it is fortunate that China has a long history of geological exploration and records, although much of this is not easily accessible to the Western world. Metallurgical exploration and workings go back to prehistoric times in China, and the oldest natural gas well in the world was dug in Sichuan Province in the 12th century. Paleontology started in China, with the studies of the scholar Yen Cheng-ching, and ideas about mountain building processes may have first originated in China as shown by the works of Chu Hsi, who described mountains as features uplifted from oceans, which then became eroded by streams, forming sedimentary basin deposits. Geology became a formal discipline in China with the establishment of a geology department at Peking University in 1909, through the efforts of Dr. F. Solger from Germany and Dr. Amadeus Grabau from the United States, who studied the stratigraphy of China for many years, and became known as the father of Chinese geology. Grabau also authored numerous books and proposed ideas on the origin of mountains, continental crust, and cycles in Earth history, based mainly on his studies in China.

GEOMORPHOLOGY

China is geomorphologically diverse, consisting of about 33 percent mountains, 25 percent plateaus (including Tibet), 20 percent basins, and 10 percent hilly terrain. In general, the land surface slopes from the high regions including Tibet in the west, to the 1,100-mile (1,800-km) coastline in the east.

Satellite image of Asia *(M-Sat Ltd. Photo Researchers, Inc.)*

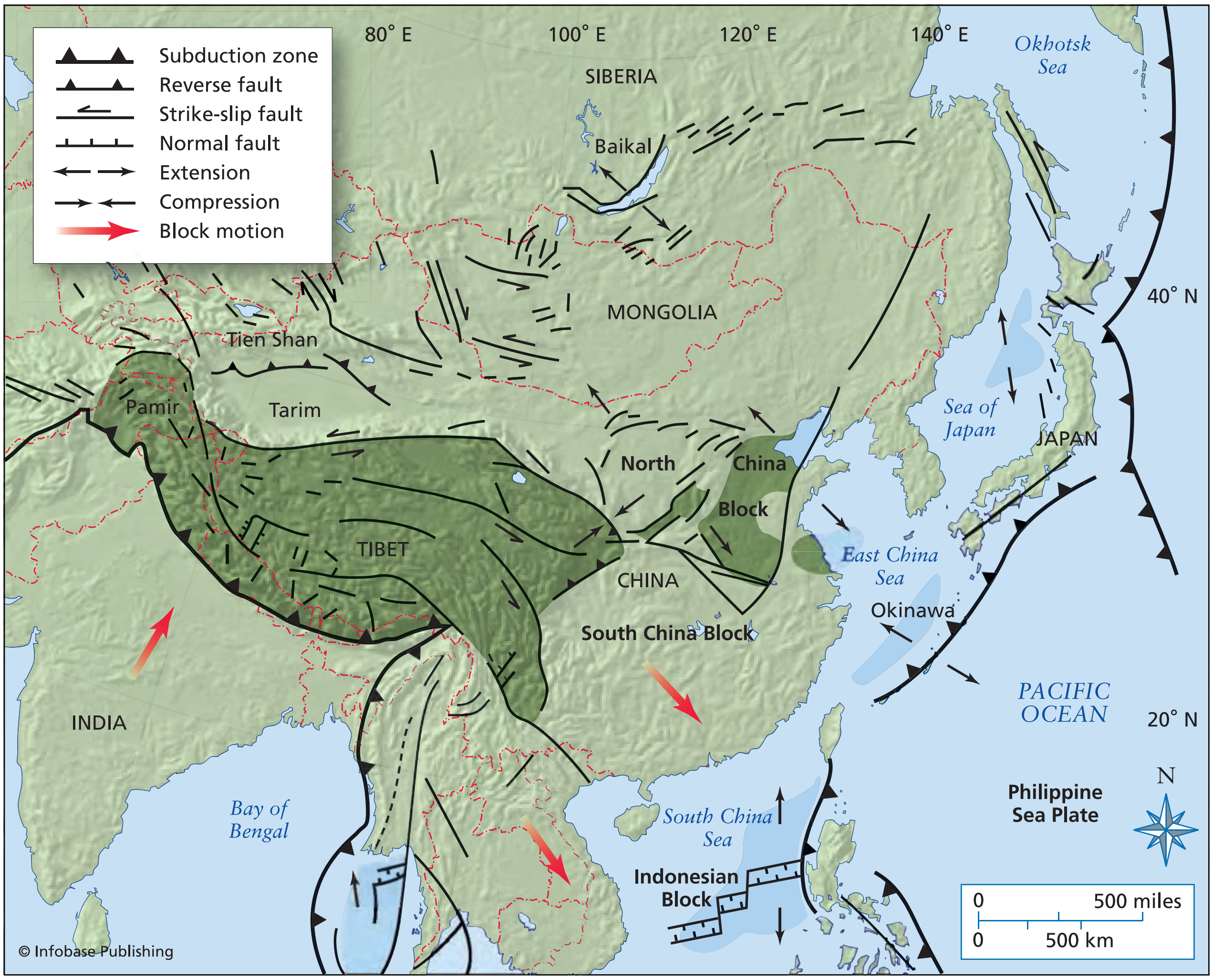
There are three main physiographic provinces of China based on elevation. The Tibetan, or Qinghai-Xizang Plateau, in the south rises generally to more than 2.5 miles (4 km) above sea level, including the Himalaya Mountains, which rise above 3.7 miles (6 km), with many peaks surpassing 5 miles (8 km) above sea level. Mount Everest (Jolmo Lungma) is the highest peak in the world, reaching 29,133 feet (8,882 m) above sea level. A series of basins and plateaus are located north and east of the Tibetan, or Qinghai-Xizang, Plateau, with elevations between 0.5 and 1.3 miles (1–2 km). The most important plateaus in this region include the Inner Mongolia Plateau or steppe, the loess plateau, and the Yunnan-Guizhou Plateau, whereas the large basins include the Sichuan, Junggar, and Tarim. Eastern China consists mostly of hills lower than a half-mile (1 km) and broad plains, including the Northeast, Lower, Northern, and Upper Chang Jiang (Yangtze River) plains, whereas the low mountains include the Shandong and Southern Hills.

Mountains (the word *shan* means “mountain” in Chinese) in China are divided into different groups according to their orientations, or trend (measured relative to geographic north). These include the E-W, or Altaid, trend, with major belts including the Tienshan, Kunlun, Tanglha, Kangkar Tesi, Qinling, Himalaya, Yinshan, and Nanling. Interestingly, the age of the activity becomes younger from north to south, reflecting processes related to the India-Asia collision. The NE-SW (Cathysian) trending mountains include the Greater Kingham, Taihang, Changbai, and Wui, mostly in eastern China. The N-S trending mountains include the Helan, Luban, and Hengduan. Other mountains trend NW-SE, such as the Karakoram and Altai Mountains in the west, and the Lesser Kinghan in the northeast.

The Tibet, or Qinghai-Xizhang, Plateau is the world’s largest region of thickened, uplifted crust; it formed in response to the collision of India with Asia after the Cretaceous. Many rivers in Asia have their source on this plateau, and changing climate conditions with loss of glacial ice imperils many of these rivers. Many tectonically controlled lakes on the Tibet Plateau have formed in fault-controlled basins largely since the Eocene. In southwestern China the Yunnan-Guizhou Plateau has an average elevation of about 1.2 miles (2 km), but decreases to the east. This uplifted plateau is comprised largely of limestones and other soluble rocks, so as the uplift proceeded and groundwater levels dropped, a spectacular karst landscape developed across much of this plateau, forming some of the world’s most impressive karst landscapes, such as the stone forest of Kunning and the karst towers of Guilin. Many Mesozoic red beds lie in the western part of this plateau. The Great Wall of China was built along the north edge of the loess plateau, which has an average elevation of 0.6 miles (1 km) over an area of 156,000 square miles (400,000 km^2), encompassing the Yinshan, Qinling, Qilian, and Taishan Mountains. Wind-blown dust and silt on the plateau and extending eastward to the Yellow Sea form the thickest and most extensive loess deposits in the world. In most places the loess is 150–250 feet (50–80 m) thick, but in places is up to 3,200 (975 m) feet thick. The dust originates in the Gobi and Ordos desert basins to the west, with much being deposited during the Quaternary, formed during the Pleistocene ice ages when strong winds blew from the NW to the SE. The plateau of Inner Mongolia has a similar height to the loess plateau, but this region is being actively extended and eroded, after a period of uplift in the Cenozoic.

China has many large basins of diverse origin. The Tarim, Junggar, and Qiadam basins in the west are relic back-arc basins developed on the margins of the Paleotethys Ocean, although the basins have complex older histories. The Tarim basin, one of the largest interior basins in the world, has a Precambrian basement, overlain by thick Mesozoic and Cenozoic rocks, whereas the Junggar basin has Paleozoic basement overlain by Mesozoic and Cenozoic basinal sequences. The Sichuan basin has a complex history, including Precambrian basement overlain by Paleozoic and Mesozoic red beds, including foreland basin deposits from the Longmen and Qinling orogens. The Ordos basin has Precambrian platformal sediments overlain by Paleozoic through Tertiary sedimentary layers. In the east the Bohai, or North China, basin is a complex rift-pull-apart basin of Paleogene age that has huge hydrocarbon reserves, including the Shenli, Dagong, and Renqin oil fields. In the north the Songliao basin is a Late Mesozoic rift basin that developed behind an active margin. On the eastern coast of China the East and South China Seas form passive margin-type basins formed in back-arc environments above the Pacific seduction system.

One of the world’s great deserts, the Gobi, located in central Asia, encompasses more than 500,000 square miles (1,295,000 km^2) in Mongolia and northern China. The desert covers the region from the Great Khingan Mountains northwest of Beijing to the Tien Shan north of Tibet, but the desert is expanding at an alarming rate, threatening the livelihood of tens of thousands of farmers and nomadic sheepherders every year. Every spring dust from the Gobi covers eastern China, Korea, and Japan, and may extend at times around the globe. Northwesterly winds have removed almost all the soil from land in the Gobi, depositing it as thick loess



Tectonic map of Asia showing the relationships between the India-Asia collision, escape of the Indonesian and South China blocks seaward, and extension from Siberia to the Pacific margin, including opening of the Sea of Japan and the South China Sea *(modeled after T. Kusky, M. Zhai, and W. J. Xiao)*

in eastern China. Most of the Gobi is situated on a high plateau resting 3,000–5,000 feet (900–1,500 m) above sea level, and it contains numerous alkaline sabkhas and sandy plains in the west. Regions in the Gobi include abundant steppes, high mountains, forests, and sandy plains. The Gobi has yielded many archaeological, paleontological, and geological finds, including early stone implements, dinosaur eggs, and mineral deposits and precious stones including turquoise and jasper.

ARCHEAN CRATONS

China includes several blocks of ancient continental crust known as cratons. These include the North China craton, South China craton (including the Cathaysia and Yangtze blocks), and the Tarim block. Parts of northeastern and southern China in these cratons are well known for Late Proterozoic–age sedimentary deposits that host some of the world's most spectacular early animal fossils. One of the best studied sequences is the Doushantuo Formation of phosphatic sedimentary rocks exposed in south China's Guizhou Province, dated to be 580–600 million years old. The Sinian fauna is therefore older than the well-known Ediacaran metazoan fauna, and is currently the oldest-known assemblage of multicellular animal fossils on the Earth. The macrofossil assemblages are associated with prokaryotic and eukaryotic microfossils, and display remarkably well-preserved cellular and tissue structures and even remnants of organic material known as kerogen. Many of the fossils are unusual acritarchs, organic walled fossils with peripheral processes such as spines, hairs, and flagellum, which cannot be confidently placed into any living plant or animal group classification. Scientists are currently debating the origin of some of the fossils, whether they may be metazoan embryos, multicellular algae, filamentous bacteria, acritarchs, or phytoplankton.

North China Craton and Tarim Block

The North China craton occupies about 1 million square miles (1.7 million km^2) in northeastern China, Inner Mongolia, the Yellow Sea, and North Korea, and apparently shares an early geological history with the poorly known Tarim block to the west. It is bounded by the Qinling-Dabie Shan orogen to the south, the Yinshan-Yanshan orogen to the north, the Longshoushan belt to the west, and the Qinglong-Luznxian and Jiao-Liao belts to the east. The North China craton includes a large area of intermittently exposed Archean crust, including circa 3.8–2.5 billion-year-old gneiss, tonalite, trondhjemite, and granodiorite. Other areas include granite, migmatite, amphibolite, ultramafite, mica schist and dolomitic marble, graphitic and other metasedimentary gneiss, banded iron formation (BIF), and metaarkose. The Archean rocks are overlain by the 1.85–1.40 billion-year-old Mesoproterozoic Changcheng (Great Wall) system. In some areas in the central part of the North China craton 2.40–1.90 billion-year-old Paleoproterozoic sequences deposited in cratonic rifts are preserved.

The North China craton is divided into two major blocks separated by the Neoarchean Central orogenic belt, in which virtually all isotopic ages on the rocks fall between 2.55 and 2.50 billion years. The Western block, also known as the Ordos block, is a stable craton with a thick mantle root, no earthquakes, low heat flow, and lack of internal deformation since the Precambrian. In contrast, the Eastern block is atypical for a craton in that it has numerous earthquakes, high heat flow, and a thin lithosphere reflecting the lack of a thick mantle root. The North China craton is one of the world's most unusual cratons in that it had a thick tectosphere (subcontinental lithospheric mantle) developed in the Archean, which was present through the Ordovician, as shown by deep xenoliths preserved in Ordovician kimberlites. The eastern half of the root, however, appears to have delaminated or otherwise disappeared during Paleozoic, Mesozoic, or Cenozoic tectonism. This is demonstrated by Tertiary basalts that bring up mantle xenoliths of normal "Tertiary mantle" with no evidence of a thick root. The processes responsible for the loss of this root are enigmatic but are probably related to the present-day high-heat flow, Phanerozoic basin dynamics, and orogenic evolution.

The Central orogenic belt includes belts of tonalite-trondhjemite-granodiorite, granite, and supracrustal sequences metamorphosed from granulite to greenschist facies. It can be traced for about 1,000 miles (1,600 km) from west Liaoning to west Henan. Widespread high-grade regional metamorphism including migmatization occurred throughout the Central orogenic belt between 2.6 and 2.5 billion years ago, with final uplift of the metamorphic terrain at 1.9–1.8 billion years ago associated with extensional tectonism or a collision on the northern margin of the craton. Amphibolite to greenschist-grade metamorphism predominates in the southeastern part of the Central orogenic belt, but the northwestern part of the orogen is dominated by granulite-facies to amphibolite-facies rocks, including some high-pressure assemblages (10–13 kilobars at 850 ± 50°C). The high-pressure assemblages can be traced for more than 400 miles (700 km) along a linear belt trending east-northeast. Internal (western) parts of the orogen are characterized by thrust-related horizontal foliations, flat-dipping shear zones, recumbent folds, and tectonically interleaved high-pressure granulite migmatite and metasediments. It is widely overlain by sediments deposited in rifts and continental shelf environments, and intruded by several dike swarms (2.4–2.5, and 1.8–1.9 billion years ago). Several large anorogenic granites with ages of 2.2–2.0 billion years are identified within the belt. Recently two linear units have been documented within the belt, including a high-pressure granulite belt in the west and a foreland-thrust fold belt in the east. The high-pressure granulite belt is separated by normal-sense shear zones from the Western block, which is overlain by thick metasedimentary sequences younger than 2.4 billion years that metamorphosed 1.86 billion years ago.

The Hengshan high-pressure granulite belt is about 400 miles (700 km) long, consisting of several metamorphic terrains, including the Hengshan, Huaian, Chengde, and west Liaoning complexes. The high-pressure assemblages commonly occur as inclusions within intensely sheared tonalite-trondhjemite-granodiorite (2.6–2.5 billion years) and granitic gneiss (2.5 billion years) and are widely intruded by K-granite (2.2–1.9 billion years) and mafic dike swarms (2.40–2.45 Ga, 1.77 billion years). Locally, khondalite and turbiditic slices are interleaved with the high-pressure granulite rocks, suggesting thrusting. The main rock type is garnet-bearing mafic granulite with characteristic plagioclase-orthopyroxene corona around the garnet, which shows rapid exhumation-related decompression. A constant-temperature decompressive pressure-temperature-time path can be documented within the rocks, and the peak pressures and temperatures are in the range of 1.2–1.0 GPa, at 1,290–1,470°F (700–800°C). At least three types of geochemical patterns are shown by mafic rocks of the high-pressure granulites, indicating a tectonic setting of active continental margin or island arc. The high-pressure granulites were formed through subduction-collision, followed by rapid rebound-extension, recorded by 2.5–2.4 billion-year old mafic dike swarms and rift-related sedimentary sequences in the Wutai Mountai-Taihang Mountain areas.

The Qinglong foreland basin and fold-thrust belt is north- to northeast-trending and is now preserved as several relict-folded sequences (Qinglong, Fuping, Hutuo, and Dengfeng). Its general sequence from bottom to top can be further divided into three subgroups of quartzite-mudstone-marble, turbidite, and molasse, respectively. The lower subgroup of quartzite-mudstone-marble is well preserved in central sections of the Qinglong foreland basin (Taihang Mountain), with flat-dipping structures, interpreted as a passive margin developed before 2.5 Ga on the Eastern block. It is overlain by lower-grade turbidite and molasse-type sediments. The western margin of Qinglong foreland basin is intensely reworked by thrusting and folding and is overthrust by the overlying orogenic complex (including the tonalitic-trondhjemitic-granodiorotic gneiss, ophiolites, accretionary prism sediments). To the east its deformation becomes weaker in intensity. The Qinglong foreland basin is intruded by a gabbroic dike complex consisting of 2.4 billion-year-old diorite and is overlain by graben-related sediments and flood basalts. In the Wutai and North Taihang basins, many ophiolitic blocks are recognized along the western margin of the foreland thrust-fold belt. These consists of pillow lava, gabbroic cumulates, and harzburgite. The largest ophiolitic thrust complex imbricated with foreland basin sedimentary rocks is up to 5 miles (10 km) long, preserved in the Wutai-Taihang Mountains.

Several dismembered Archean ophiolites have been identified in the Central orogenic belt, including some in Lioning Province, at Dongwanzi, north of Zunhua, and at Wutai Mountain. The best studied of these are the Dongwanzi and Zunhua ophiolitic terranes. The Zunhua structural belt of eastern Hebei Province preserves a cross section through most of the northeastern part of the Central orogenic belt. This belt is characterized by highly strained gneiss, banded iron formation, 2.6–2.5 billion-year-old greenstone belts, and mafic to ultramafic complexes in a high-grade ophiolitic mélange. The belt is intruded by widespread 2.6–2.5 billion-year-old tonalite-trondhjemite gneiss and 2.5 billion-year-old granites, and is cut by ductile shear zones. The Neoarchean high-pressure granulite belt (Chengde-Hengshan HPG) strikes through the northwest part of the belt. The Zunhua structural belt is thrust over the Neoarchean Qianxi-Taipingzhai granulite-facies terrane, consisting of high-grade metasedimentary to charnockitic gneiss forming several small dome-like structures southeast of the Zunhua belt. The Zunhua structural belt clearly cuts across the dome-like Qian'an-Qianxi structural patterns to the east. The Qian'an granulite-gneiss dome (3.8–2.5 billion years old) forms a large circular dome in the southern part of the area and is composed of tonalitic-trondhjemitic gneiss and biotite granite. Mesoarchean (2.8–3.0 billion years old) and Paleoarchean (3.50–3.85 billion years old) supracrustal sequences outcrop in the eastern part of the region. The Qinglong Neoarchean amphibolite to greenschist-facies supracrustal sequence strikes through the center of the area and is interpreted to be a foreland fold-thrust belt, intruded by large volumes of 2.4 billion-year-old diorite in the east. The entire North China craton is widely cut by at least two Paleoproterozoic mafic dike swarms (2.5–2.4, 1.8–1.7 billion years old), associated with regional extension. Mesozoic-Cenozoic granite, diorite, gabbro, and ultramafic plugs occur throughout the NCC and form small intrusions in some of the belts.

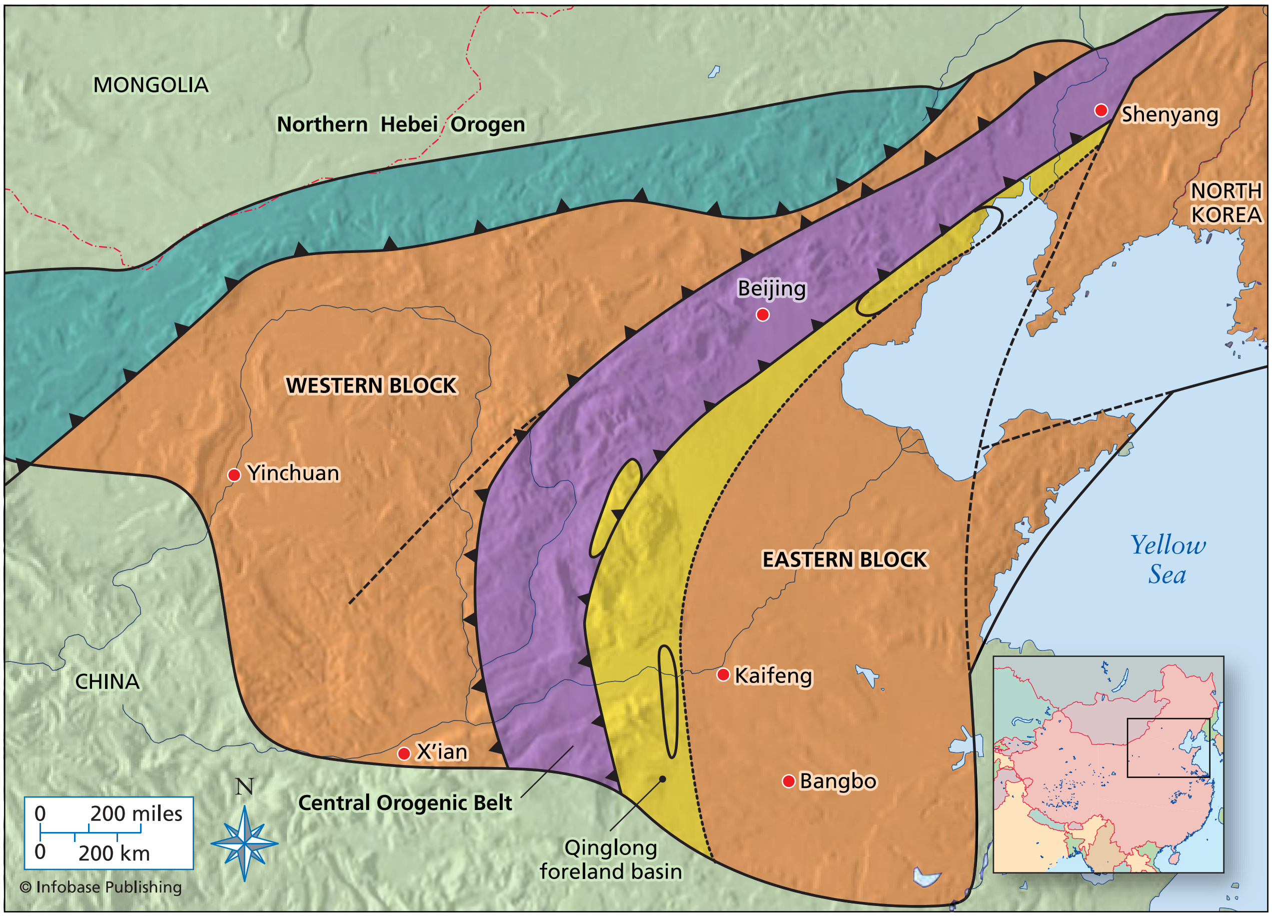
The largest well-preserved sections of the Dongwanzi ophiolite are located approximately 120 miles (200 km) northeast of Beijing in the northeastern part of the Zunhua structural belt, near the villages of Shangyin and Dongwanzi. The belt consists of prominent amphibolite-facies mafic-ultramafic complexes in the northeast sector of the Zunhua structural belt. The southern end of the Dongwanzi ophiolite belt near Shangyin is complexly faulted against granulite-facies gneiss, with both thrust faults and younger normal faults present. The main section of the ophiolite dips steeply northwest, is approximately 30 miles (50 km) long, and is 3–6 miles (5–10 km) wide. A U/Pb-zircon age of 2.505 billion years for two gabbro samples from the Dongwanzi ophiolite shows that this is the oldest, relatively complete ophiolite known in the world. Parts of the central belt, however, are intruded by a mafic/ultramafic Mesozoic pluton with related dikes.

A high-temperature shear zone intruded by the 2.4 Ga old diorite and tonalite marks the base of the ophiolite. Exposed ultramafic rocks along the base of the ophiolite in the ophiolite include strongly foliated and lineated dunite and layered harzburgite. Aligned pyroxene crystals and generally strong deformation of serpentinized harzburgite resulted in strongly foliated rock. Harzburgite shows evidence for early high-temperature deformation. This unit is interpreted to be part of the lower residual mantle, from which the overlying units were extracted.

The cumulate layer represents the transition zone between the lower ultramafic cumulates and upper mafic assemblages. The lower part of the sequence consists of layers of pyroxenite, dunite, wehrlite, lherzolite and websterite, and olivine gabbro-layered cumulates, all formed by heavy crystals sinking through the magma and settling on the bottom of the magma chamber. Many layers grade from dunite at the base, through wehrlite, and are capped by clinopyroxene. Basaltic dikes cut through the cumulates and are similar mineralogically and texturally to dikes in the upper layers.

The gabbro complex of the ophiolite is up to three miles (5 km) thick and grades up from a zone of mixed layered gabbro and ultramafic rocks to one of strongly layered gabbro that is topped by a zone of isotropic gabbro. Thicknesses of individual layers vary from centimeter to meter scale and include clinopyroxene and plagioclase-rich layers. Layered gabbros from the lower central belt alternate between fine-grained layers of pyroxene and metamorphic biotite that are separated by layers of metamorphic biotite intergrown with quartz. Biotite and pyroxene layers show a random orientation of grains. Coarse-grained veins of feldspar and quartz are concentrated along faults and fractures. Plagioclase feldspar shows core replacement and typically has irregular grain boundaries. The gabbro complex of the ophiolite has been dated by the U-Pb method on zircons to be 2,504 ± 2 million years old.

The sheeted dike complex is discontinuous over several kilometers. More than 70 percent of the dikes are unusual in that only one half of each dike is preserved. In most tectonic settings dikes have fine-grained chill margins on both margins where they intruded and cooled against country rocks, crystallizing quickly and forming two parallel chill margins with finer-grained crystals than in the slower-cooling interior of the dikes. Dikes in ophiolites often show dikes with only one chill margin, where new dikes successively intrude the center of the previously intruded dike, in a setting where the crust is being extended and filled by new dikes. When the next dike intruded, it intruded along the center of the last dike, and this happened several times in a row, leaving a dike complex with chill margins preserved preferentially on one side. One-way chill margins are preferentially preserved on their northeast side of the dikes in the Dongwanzi ophiolite. Gabbro screens are common throughout the complex and increase in number and thickness downward, marking the



Tectonic map of the North China craton showing the eastern and western blocks, 2.5 billion-year-old Central Orogenic Belt, and the 1.9 billion-year-old North Hebei Orogen *(modeled after T. Kusky and J. H. Li)* transition from the dike complex to the fossil magma chamber. In some areas the gabbro is cut by basaltic-diabase dikes, but in others it cuts through xenoliths of diabase, suggesting comagmatic formation.

The upper part of ophiolite consists of altered and deformed pillow basalts, pillow breccias, and interpillow sediments (chert and banded iron formations). Many of the pillows are interbedded with more massive flows and cut by sills; however, some well-preserved pillows show typical lower cuspate and upper lobate boundaries that define stratigraphic younging. Pyroxenes from pillow lavas from the ophiolite have been dated by the Lu-Hf method to be 2.5 billion years old, the same age as estimated for the gabbro and mantle sections.

The base of the ophiolite is strongly deformed, and intruded by the 2.391 billion-year-old Cuizhangzi diorite-tonalite complex. The Dongwanzi ophiolite is associated with a number of other amphibolite-facies belts of mafic plutonic and extrusive igneous rocks in the Zunhua structural belt. These mafic-to-ultramafic slices and blocks can be traced regionally over a large area from Zunhua to West Liaoning (about 120 miles or 200 km). Much of the Zunhua structural belt is interpreted as a high-grade ophiolitic mélange, with numerous tectonic blocks of pillow lava, BIF, dike complex, gabbro, dunite, serpentinized harzburgite, and podiform chromitite in a biotite-gneiss matrix, intruded extensively by tonalite and granodiorite. Cross-cutting granite has yielded an age of 2.4 billion years. Blocks in the mélange correlate with the Dongwanzi and other ophiolitic fragments in the Zunhua structural belt. This correlation is supported by the isotopic system of Rhenium (Re)-Osmium (Os), since Re-Os age determinations on several of these blocks reveal that they are 2.54 billion years old.

The Eastern and Western blocks of the North China craton collided at 2.5 billion years ago during an arc/continent collision, forming a foreland basin on the Eastern block, a granulite facies belt on the Western block, and a wide orogen between the two blocks. This collision was followed rapidly by post-orogenic extension and rifting that formed mafic dike swarms and extensional basins along the Central orogenic belt, and led to the development of a major ocean along the north margin of the craton. An arc terrane developed in this ocean and collided with the north margin of the craton by 2.3 Ga, forming an 850-mile (1,400-km) long orogen known as the Inner Mongolia–Northern Hebei orogen. A 1,000-mile (1,600-km) long granulite-facies terrain formed on the southern margin of this orogen, representing a 120-mile (200-km) wide uplifted plateau formed by crustal thickening. The orogen was converted to an Andean-style convergent margin between 2.20 and 1.85 billion years ago, recorded by belts of plutonic rocks, accreted metasedimentary rocks, and a possible back arc basin. A pulse of convergent deformation is recorded at 1.9–1.85 billion years across the northern margin of the craton, perhaps related to a collision outboard of the Inner Mongolia–Northern Hebei orogen, and closure of the back arc basin. This event caused widespread deposition of conglomerate and sandstone of the basal Changcheng Series in a foreland basin along the north margin of the craton. At 1.85 billion years the tectonics of the North China craton became extensional, and a series of aulacogens and rifts propagated across the craton, along with the intrusion of mafic dike swarms. The northern granulite facies belt underwent retrograde metamorphism, and was uplifted during extensional faulting. High-pressure granulites are now found in the areas where rocks were metamorphosed to granulite facies and exhumed two times, at 2.5 and 1.8 billion years ago, respectively, exposing rocks that were once at lower crustal levels. Rifting led to the development of a major ocean along the southwest margin of the craton, where oceanic records continue until 1.5 billion years ago.

South China Craton

The South China craton is divided into the Yangtze craton and the Cathaysia block, joined together in a plate collision in the late Mesoproterozoic. Radiometric dating of two ophiolite suites in the eastern part of the suture between the Yangtze and Cathaysia blocks gives ages of 1.03 to 1.02 billion years for the age of this collision. Late Mesoproterozoic suture zones have been also reported from the northwestern and northern margins of the Yangtze block. An ophiolitic mélange in western Sichuan (the northwestern margin) that contains gabbro and diabase has been dated isotopically to be 1.01 billion years old. Zircon ages of 1.3 and 1.0 billion years have been determined from igneous intrusions at the northern margin of the Yangtze block. The late Mesoproterozoic continental collision belts in and around the South China block corresponded to one of the central Grenvillian sutures of the Rodinian supercontinent that brought together Australia, Yangtze, and Cathaysia-Laurentia at about 1 billion years ago.

The stratigraphy, tectonic evolution, and paleomagnetic features of the southern North China craton differ from those of the South China craton and suggest that north China became a part of the Rodinia supercontinent about 1 billion years ago, when the southern border of the North China craton lay adjacent to Siberia. The south and north China blocks became parts of the Rodinia supercontinent independently about 1 billion years ago.

The breakup of Rodinia was probably initiated by a mantle plume that rose beneath the supercontinent 820 million years ago. The Kangdian rift in the southwestern border of the South China block and the Nanhua rift along the boundary between the Yangtze and Cathaysia blocks formed as a result of the breakup of Rodinia. The 800–700 million-year-old intrusion ages of granitic gneisses in the northern border of the South China block are also associated with rifting of the South China block from Rodinia. The separation of the South China block from Rodinia must have occurred after 750 million years ago. Likewise, on the southern borders of the North China block, rather weak magmatic activity and metamorphism at about 800–600 million years ago has been identified, which may relate to the rifting of the North China block from Rodinia.

Following the breakup of Rodinia during the late Neoproterozoic, several microcontinents and immature island arcs amalgamated through collision and accretion to form Gondwana during the Pan-African orogeny. The South and North China cratons probably converged with each other during the early Cambrian and lay close to Australia by the mid and late Cambrian. The Paleo-Tethys Ocean opened in the Devonian, moving the North and South China blocks northward, and the Paleo-Tethys Ocean between two blocks disappeared in the Middle Triassic by subduction of all oceanic crust in the ocean. The presence of 450–400 million-year-old ophiolites, arc-related 470–435 million-year-old metamorphism, and 210–330 million-year-old eclogites in the Qinling-Dabie-Sulu collision belt indicate that opening of the Paleo-Tethys had started in the mid-Ordovician instead of the Devonian.

CENTRAL ASIAN OROGENIC BELT

The Paleoasian, or Turkestan, Ocean was present on the northern side of the North China craton and Tarim block throughout the Paleozoic, with Paleotethys to the south. Several subduction zones were active during this interval, leading to continental growth through accretion of terranes along the northern margin of the cratons and the generation of arc-magmas. These terranes north of the Archean cratons host more than 900 late Paleozoic to Early Triassic plutons, formed during closure of the Paleo-Asian Ocean at the end of the Permian. Closure is marked by the Solonker suture and 300–250 million-year-old south-directed subduction beneath the accreted terranes along the northern side and the northern margin of the cratonic blocks. Continued convergence from the north during the Triassic and Jurassic caused postcollisional thrusting and considerable crustal thickening on the northwest side of the cratons. The northeastern margin of the North China craton with a Permian shelf sequence collided with the Khanka block in the Late Permian to Early Triassic, as indicated by syncollisional granites. Many of the subsequent later Mesozoic granitoids, metamorphic core complexes, and extensional basins, located south of the Solonker suture in the northern part of the craton and the adjacent Paleozoic accretionary orogen, may be related to postcollisional Jura-Cretaceous collapse of the massive Himalayan-style Solonker orogen and plateau.

DABIE SHAN–SULU TONGBAI CENTRAL CHINA OROGEN

The Qinling-Dabie-Sulu, or Dabie Shan, is the world's largest ultrahigh pressure metamorphic belt, containing Triassic (220–240 Ma) high-pressure, low-temperature (eclogite) facies metamorphic rocks formed during the collision of the North and South China cratons. Most remarkably, the orogen contains coesite and diamond-bearing eclogite rocks, indicating metamorphic burial to depths exceeding 60 miles (100 km). The Dabie Shan metamorphic belt stretches from the Tanlu fault zone between Shanghai and Wuhan, approximately 1,250 miles (2,000 km) to the west northwest to the Qaidam basin north of the Tibetan Plateau. The orogen is only 30–60 miles (50–100 km) wide in most places, and it separated the North China craton on the north from the Yangtze craton (also called the South China block) on the south. A small tectonic block or terrane known as the South Qinling is wedged between the North and South China cratons in the orogen and is thought to have collided with the North China craton in the Triassic, before the main collision.

The Qinling-Dabie-Sulu orogen is marked by numerous terranes forming the irregular suture between the North China and South China cratons. It is a major part of the E-W-trending Central China orogen that extends for 900 miles (1,500 km) eastward from the Kunlun Range, to the Qinling Range, and then 370 miles (600 km) farther east through the Tongbai-Dabie Range. Its easternmost extent, offset by movement along the Tan-Lu fault system, continues northeastward through the Sulu area of the Shandong Peninsula then into South Korea. The Sulu belt may extend through the southern part of South Korea. The intermittent presence of ultrahigh-pressure diamonds, eclogites, and felsic gneisses indicates very deep subduction along a cumulative 2,500-mile (> 4,000-km) long zone of collisional orogenesis.

The rifting and collisional history throughout the Paleozoic of the North China and Tarim cratons with blocks and orogens to the south, such as the North Qinling terrane, the South Qinling terrane, and eventually (in the Triassic) the South China craton, have been complicated and controversial. In the early Paleozoic northward subduction of the Qaidam-South Tarim plate (possibly connected with the South China plate) took place beneath the active southern margin of the NCC. The North China craton, probably together with the Tarim block, collided with the South Tarim-Qaidam block in the Devonian, then with the South China block in the Permo-Triassic. This latter collision resulted in exposure of ultrahigh-pressure rocks from approximately 60–120 miles (100–200 km) depth in the Dabie Shan, and westward sliding or escape of the South Tarim-Qaidam block, and caused uplift of a large plateau (Huabei Plateau) in the eastern North China craton. Younger extrusion tectonics related to Himalayan collisions farther west resulted in approximately 300 miles (500 km) of left-lateral motion along the Altyn-Tagh fault, separating the North China craton from the South Tarim-Qaidam block, slicing and sliding to the west the arc that formed on the southern margin of the craton during early Paleozoic subduction.

The terrane accretion and eventual "continent-continent" collision along the southern margin of the North China and Tarim cratons are defined by a geometrically irregular suture, defining a diachronous convergence with a complex spatial and temporal pattern. Many models of extrusion tectonics, such as eastward, vertical (upward), and lateral, have been proposed for the Qinling-Dabie orogen in the last decade. Vertical movement along a paleosubduction zone was important to Triassic uplift of the ultra-high-pressure rocks in the eastern part of the orogen. An orogen-parallel, eastward extrusion occurred diachronously between 240 and 225–210 Ma. Cretaceous to Cenozoic unroofing was initially dominated by eastward tectonic escape in the early Cretaceous and then by Pacific subduction in the mid-Cretaceous. The Triassic Dabie high-pressure (HP)-UHP metamorphic rocks were originally located beneath the Foping dome, located in the narrowest part of the Qinling belt, and these rocks were extruded eastward to their present-day location.

TIBETAN PLATEAU

The Tibetan Plateau is the largest high area of thickened continental crust on Earth, with an average height of 16,000 feet (4,880 m) over 470,000 square miles (1,220,000 km^2). Bordered on the south by the Himalayan Mountains, the Kunlun Mountains in the north, the Karakoram on the west, and the Hengduan Shan on the east, Tibet is the source of many of the largest rivers in Asia. The Yangtze, Mekong, Indus, Salween, and Brahmaputra Rivers all rise in Tibet, and flow through Asia, forming the most important source of water and navigation for huge regions.

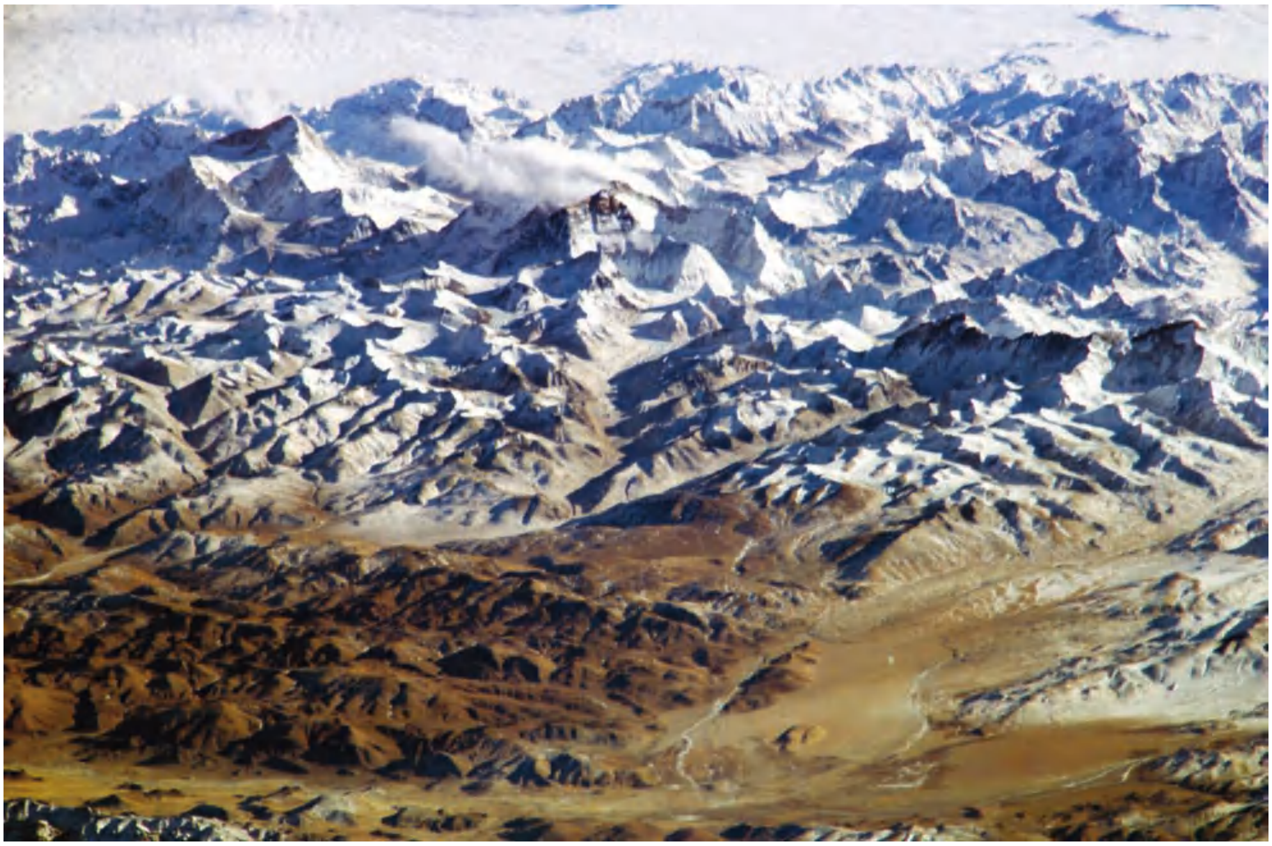
Southern Tibet merges into the foothills of the northern side of the main ranges of the Himalaya, but are separated from the mountains by the deeply incised river gorges of the Indus, Sutlej, and Yarlung Zangbo (Brahmaputra) Rivers. Central and northern Tibet consists of plains and steppes that are about 3,000 feet (1,000 m) higher in the south than the north. Eastern Tibet includes the Transverse ranges (the Hengduan Shan) that are dissected by major faults in the river valleys of the northwest-southeast–flowing Mekong, Salween, and Yangtze Rivers.

Tibet has a high plateau climate, with large diurnal and monthly temperature variations. The center of the plateau has an average January temperature of 32°F (0°C), and an average June temperature of 62°F (17°C). The southeastern part of the plateau is affected by the Bay of Bengal summer monsoons, whereas other parts of the plateau experience severe storms in fall and winter months.

Geologically, the Tibetan Plateau is divided into four terranes, including the Himalayan terrane in the south, and the Lahasa terrane, the Qiangtang terrane, and Songban-Ganzi composite terrane in the north. The Songban-Ganzi terrane includes Triassic flysch and Carboniferous-Permian sedimentary rocks, and a peridotite-gabbro-diabase sill complex that may be an ophiolite, overlain by Triassic flysch. Another fault-bounded section includes Paleozoic limestone and marine clastics, probably deposited in an extensional basin. South of the Jinsha suture, the Qiangtang terrane contains Precambrian basement overlain by Early Paleozoic sediments that are up to 12 miles (20 km) thick. Western parts of the Qiangtang terrane contain Gondwanan tillites, and Triassic-Jurassic coastal swamp and shallow marine sedimentary rocks. Late Jurassic–Early Cretaceous deformation uplifted these rocks, before they were unconformably overlain by Cretaceous strata.

The Lhasa terrane collided with the Qiangtang terrane in the Late Jurassic and formed the Bangong suture, containing flysch and ophiolitic slices, that now separates the two terranes. It is a composite terrane containing various pieces that rifted from Gondwana in the Late Permian. Southern parts of the Lhasa terrane contain abundant Upper Cretaceous to Paleocene granitic plutons and volcanics, as well as Paleozoic carbonates, and Triassic-Jurassic shallow marine deposits. The center of the Lhasa terrane is similar to the south but with fewer magmatic rocks, whereas the north contains Upper Cretaceous shallow marine rocks that onlap the Upper Jurassic–Cretaceous suture.

The Himalayan terrane collided with the Lhasa terrane in the Middle Eocene, forming the ophiolite-decorated Yarlungzangbo suture. Precambrian metamorphic basement is thrust over Sinian through Tertiary strata, including Lower Paleozoic carbonates and Devonian clastics, overlain unconformably by Permo-Carboniferous carbonates. The Himalayan terrane contains Lower Permian Gondwanan flora,



An 80-mile (130-km) wide view of the Himalayas from *International Space Station,* January 28, 2004—Mount Everest is shown in the upper center, Makalu is at the top left. The view looks south: Tibet is at the bottom, and Nepal is the land beyond Everest. *(NASA/Photo Researchers, Inc.)*

and probably represents the northern passive margin of Mesozoic India, with carbonates and clastics in the south, thickening to an all clastic continental rise sequence in the north.

The Indian plate rifted from Gondwana and started its rapid (3.2–3.5 inches per year, 80–90 mm/yr) northward movement about 120 million years ago. Subduction of the Indian plate beneath Eurasia until about 70 million years ago formed the Cretaceous Kangdese batholith belt, containing diorite, granodiorite, and granite. Collision of India with Eurasia at 50–30 million years ago formed the Lhagoi-Khangari belt of biotite and alkali granite, and the 20–10 million-year-old Himalayan belt of tourmaline-muscovite granites.

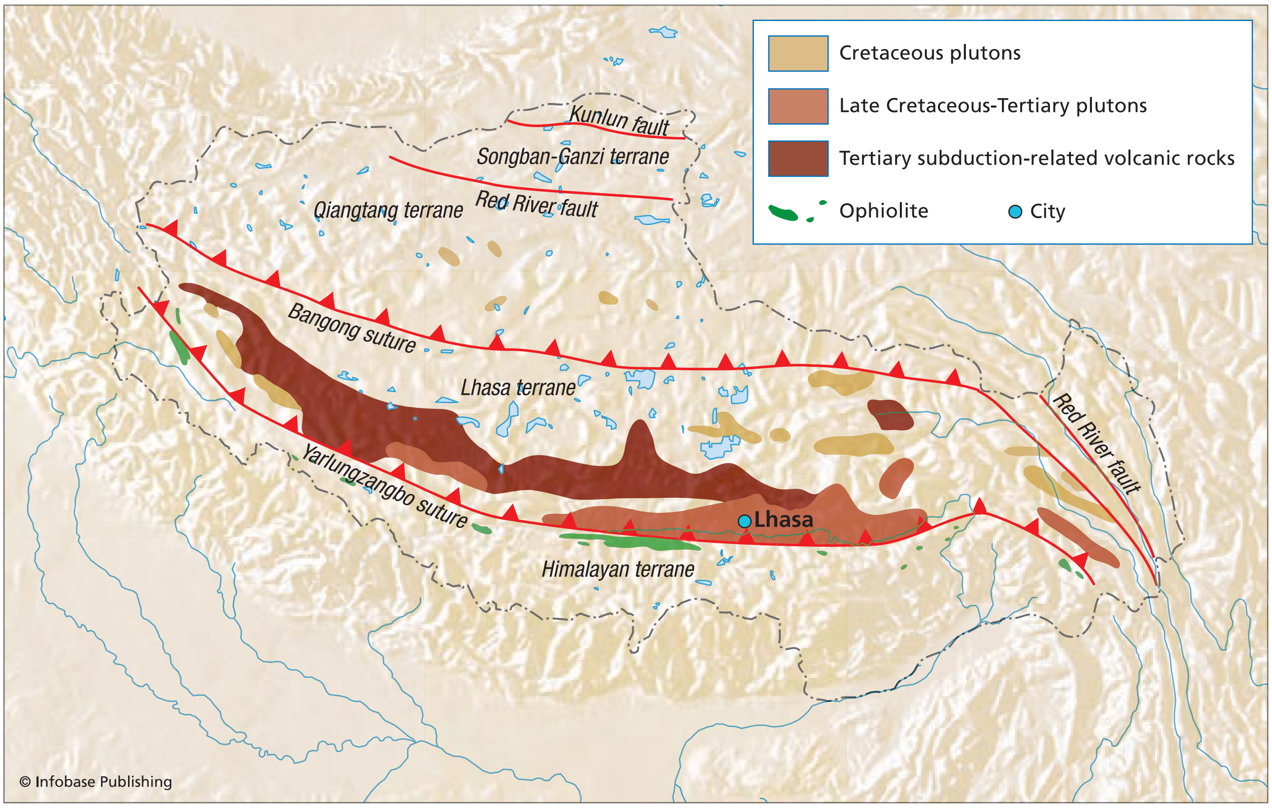
Tertiary faulting in Tibet is accompanied by volcanism, and the plateau is presently undergoing east-west extension with the formation of north-south graben associated with hot springs, and probably deep magmatism. Seismic reflection profiling has detected some regions with unusual characteristics beneath some of these grabens, interpreted by some seismologists as regions of melt or partially molten crust.

Much research has focused on the timing of the uplift of the Tibetan Plateau and modeling the role this uplift has had on global climate. The plateau strongly affects atmospheric circulation, and many models suggest that the uplift may contribute to global cooling and the growth of large continental ice sheets in latest Tertiary and Quaternary times. In addition to immediate changes to air-flow patterns around the high plateau, the uplift of large amounts of carbonate platform and silicate rocks exposes them to erosion. The weathering of these rocks causes the exposed rocks to react with atmospheric carbon dioxide, which combines these ions to produce bicarbonate ions such as are used to form calcium carbonate ($CaCO_3$), drawing down the atmospheric carbon dioxide levels and contributing to global cooling.

The best estimates of the time of collision between India and Asia is between 54 and 49 million years ago. Since then convergence between India and Asia has continued, but at a slower rate of 1.6–2.0 inches per year (40–50 mm/yr), and this convergence has resulted in intense folding, thrusting, shortening, and uplift of the Tibetan Plateau. Timing the uplift to specific altitudes is difficult, and considerable debate has centered on how much earlier than 50 million years ago the plateau reached its current height of 16,404 feet (5 km). Most geologists would now agree that this height was attained by 13.5 million years ago, and that any additional height increase is unlikely since the strength of the rocks at depth has been exceeded, and the currently active east-west extensional faults are accommodating any additional height increase by allowing the crust to flow laterally.

When the plateau reached significant heights, it began to deflect regional air-flow currents that in turn deflect the jet streams, causing them to meander and change course. Global weather patterns were strongly changed. In particular, the cold polar jet stream is now at times deflected southward over North America, northwest Europe, and other places where ice sheets have developed. The uplift increased aridity in Central Asia by blocking moist airflow across the plateau, leading to higher summer and cooler winter temperatures. The uplift also intensified the Indian Ocean monsoon over what it was before the uplift, because the height of the plateau intensifies temperature-driven atmospheric flow as higher and lower pressure systems develop over the plateau during winter and summer. This has increased the amount of rainfall along the front of the Himalayan Mountains, where some of the world's heaviest rainfalls have been reported, as the Indian monsoons are forced over the high plateau. The cooler temperatures on the plateau led to the growth of glaciers, which in turn reflect back more sunlight, further adding to the cooling effect.

Paleoclimate records show that the Indian Ocean monsoon underwent strong intensification 7–8 million years ago, in agreement with some estimates of the time of uplift, but younger than other estimates. The effects of the uplift would be different if the uplift had occurred rapidly in the Late Pliocene-Pleistocene (as suggested by analysis of geomorphology, paleokarst, and mammal fauna), or if the uplift had occurred gradually since the Eocene (based on lake sediment analysis). Most geologists accept analysis of data that suggest that uplift began about 25 million years ago, with the plateau reaching its current height by 14 or 15 million years ago. These estimates are based on the timing of the start of extensional deformation that accommodated the exceptional height of the plateau, sedimentological records, and uplift histories based on geothermometry and fission track data.



Map of Tibet showing different terranes that make up the high plateau

HIMALAYA MOUNTAINS

The world's tallest mountains, as well as those exhibiting the greatest vertical relief over short distances, form the Himalaya range that developed in the continent-continent collision zone between India and Asia. The range extends for more than 1,800 miles (3,000 km) from the Karakorum near Kabul (Afghanistan), past Lhasa in Tibet, to Arunachal Pradesh in the remote Assam province of India. Ten of the world's 14 peaks that rise to more than 26,000 feet (8,000 m) are located in the Himalaya, including Mount Everest, 29,035 feet (8,850 m), Nanga Parbat, 26,650 feet (8,123 m), and Namche Barwa, 25,440 feet (7,754 m). The rivers that drain the Himalaya include some with the highest sediment outputs in the world, including the Indus, Ganges, and Brahmaputra. The Indo-Gangetic plain on the southern side of the Himalaya represents a foreland basin filled by sediments eroded from the mountains and deposited on Precambrian and Gondwanan rocks of peninsular India. The northern margin of the Himalaya is marked by the world's highest and largest uplifted plateau, the Tibetan Plateau.

The Himalaya is one of the youngest mountain ranges in the world but has a long and complicated history. This history is best understood in the context of five main structural and tectonic units within the ranges. The Subhimalaya includes the Neogene Siwalik molasse, bounded on the south by the Main Frontal Thrust, which places the Siwalik molasse over the Indo-Gangetic plain. The Lower or Subhimalaya is thrust over the Subhimalaya along the Main Boundary Thrust and consists mainly of deformed thrust sheets derived from the northern margin of the Indian shield. The High Himalaya is a large area of crystalline basement rocks, thrust over the Subhimalaya along the Main Central Thrust. Further north, the High Himalaya sedimentary series, or Tibetan Himalaya, consists of sedimentary rocks deposited on the crystalline basement of the High Himalaya. Finally, the Indus-Tsangpo suture represents the suture between the Himalaya and the Tibetan Plateau to the north.

Sedimentary rocks in the Himalaya record events on the Indian subcontinent, including a thick Cambrian-Ordovician through Late Carboniferous/Early Permian Gondwanan sequence, followed by rocks deposited during rifting and subsidence events on the margins of the Tethys and Neotethys Oceans. The collision of India with Asia was in progress by the Early Eocene. This collision exposed the diverse rocks in the Himalaya, revealing a rich geologic history that extends back to the Precambrian, where shield rocks of the Aravalli Delhi cratons are intruded by 500 million-year-old granites. Subduction of Tethyan oceanic crust along the southern margin of Tibet formed an Andean-style arc represented by the Transhimalaya batholith that extends west into the Kohistan island arc sequence, in a manner similar to the Alaskan range—Aleutians of western North America. The obduction of ophiolites and high-pressure (blueschist facies) metamorphism dated to have occurred around 100 million years ago is believed to be related to this subduction. Thrust stacks began stacking up on the Indian subcontinent, and by the Miocene, deep attempted intracrustal subduction of the Indian plate beneath Tibet along the Main Central Thrust formed high-grade metamorphism and generated a suite of granitic rocks in the Himalaya. After 15–10 million years ago, movements were transferred to the south to the Main Frontal Thrust, which is still active.

CENOZOIC TECTONICS OF ASIA

Many large Mesozoic and Cenozoic basins cover the eastern North China craton and extend northward into Mongolia. The development of these large basins was concentrated in two time periods, the Jurassic to Cretaceous and the Cretaceous to present. An overall NW-SE–trending extensional stress field during formation of these basins was related to changes in convergence rates of India-Eurasia and Pacific-Eurasia combined with mantle upwelling. Two stages of basin formation may have been related to lithosphere erosion that began in the Early Jurassic or to subduction of the Kula plate beneath eastern China in Jurassic-Cretaceous time and later subduction of the Pacific plate. Geophysical and geochemical data show that the areas of thinner lithosphere correspond to the deepest Cenozoic basins. Kimberlites found in these basins provide the only direct source of information about the underlying mantle.

The Cretaceous-Tertiary Tieling basin in northern Liaoning Province hosts Mesozoic-Tertiary kimberlites. Phanerozoic lithosphere beneath the Tan-Lu fault was replaced by hotter, more fertile material that may be related to the Tertiary rifting of the Shanxi highlands. Furthermore, the Eocene Luliang kimberlites imply Phanerozoic-type mantle was in place by the end of the Cretaceous. Another kimberlite within a narrow Cenozoic basin lying along the Tan-Lu fault in Tieling County shows similar Phanerozoic-type mantle related to rifting. Garnet temperatures at shallow depths indicate that significant cooling occurred after the Phanerozoic mantle was emplaced beneath this area.

Cenozoic Extension in the Shanxi Graben and Bohai Sea Basins

Cenozoic extensional deformation in the central North China craton is localized in two elongate graben systems surrounding the Ordos block: the S-shaped Weihe-Shanxi graben system (Shanxi grabens for short) to the east and southeast and the arc-shaped Yinchuan-Hetao graben system to the northwest. The southwestern margin of this block corresponds to a zone of compression, through which the North China craton is in direct contact with the Tibetan Plateau. The subsidence in these grabens began during the Eocene and extended to the whole graben system during the Pliocene. The Shanxi graben system was the last to be initiated in northern China at about 6 million years ago. These two extensional domains show differences in the thickness of the crust and lithosphere, which change sharply across the eastern edge of the Taihangshan Massif on the eastern side of the Shanxi graben system. The Shanxi graben system consists of a series of en echelon depressions bounded by normal faults. The S-shaped geometry of the Shanxi graben system has two broad extensional domains in the north and south, and a narrow transtensional zone in the middle. Satellite image interpretation and field analyses of active fault morphology show predominantly active normal faulting. Right-lateral strike-slip motion along faults that strike more northerly suggest that the Shanxi graben system is a right lateral transtensional shear zone, or alternatively, an oblique divergent boundary between blocks within northern China.

North-northeast–oriented initial extension along the footwall of range-frontal fault zones in northern Shanxi predates the Pliocene opening of the Shanxi graben and may be coincident with the Miocene Hannuoba basalt flow. The direction of extension that prevailed during the initiation and evolution of the Shanxi graben system shows a northward clockwise rotation, from N300–330°E along its southern and middle portion to N330–350°E across the northern part. Late Quaternary active fault morphology implies that the opening of the Shanxi graben system proceeded by northward propagation. This opening mode reflects a counterclockwise rotation of the Taihangshan Massif with respect to the Ordos block around a pole located outside the block.

During the Miocene, the regions of rifting in northern China were subjected to regional subsidence and the eruption of widespread basalt flows. Basalt volcanism, dated to have occurred between 25 and 10 million years ago, was extensive in Mongolia and eastern China, including in the areas of the above rifts. This volcanism was related to extension in response to rollback of the subducted Pacific plate beneath eastern Asia. Miocene normal faulting occurred particularly in the offshore part of the Bohai Sea basin, where this normal fault set strikes more easterly.

Miocene extension in north China may have shared a common mechanism with that of the opening of the Japan Sea. First, the opening of the Japan Sea began at the end of the Oligocene, around 28 million years ago, or earlier to the Middle Miocene, about 18 million years ago; the youngest dredged basaltic volcanic rocks were dated as 11 million years old. Second, the spreading direction of the Japan Sea is roughly N-S to NNE-SSW, consistent with the Miocene stretching direction in northern China. Finally, the same extensional stress regime trending ENE to NE has been documented in northeastern Japan (east of the Japan Sea) based on the direction of dike swarms and dated at 20–15 million years old.

PACIFIC PLATE SUBDUCTION

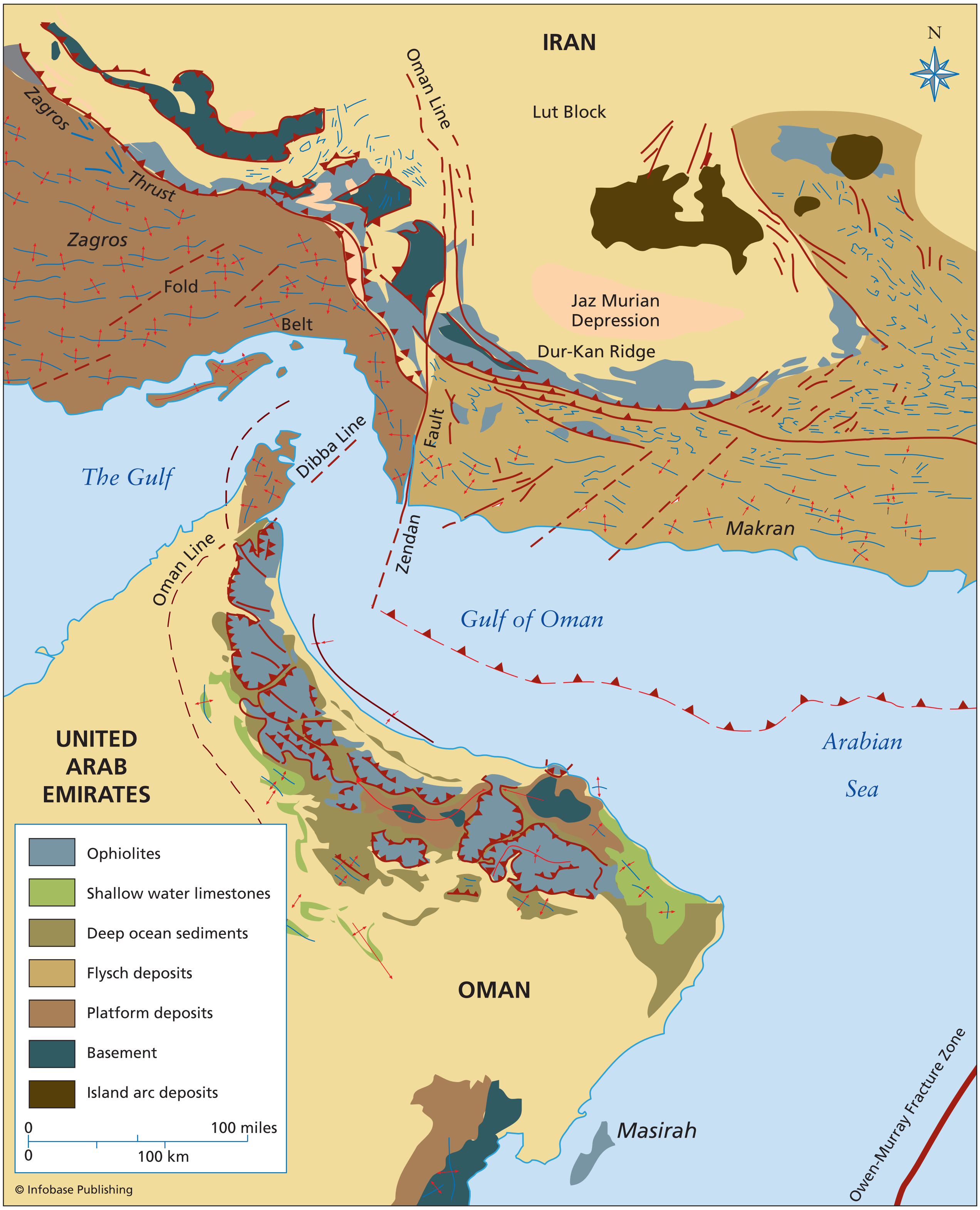
Subduction along the Pacific margin of China was active from 200 to 100 Ma, soon after closure of the ocean basins on the northern side of the North China craton. Westward-directed oblique subduction was responsible for the generation of arc magmas, deformation, and possibly mantle hydration during this interval. Although the duration and history of Mesozoic subduction beneath the eastern margin of China is not well known, the active margin stepped outward by the Cenozoic, from which a better record is preserved. Numerous plate reconstructions for the Cenozoic of Asia and the eastern Pacific basin show that a wide scenario of different plates, convergence rates, and angles of subduction definitely relate to some of the processes of basin formation, magmatism, and deformation in easternmost China.

The long-lived subduction beneath eastern China may have led to the formation of the many Mesozoic basins in this region. When oceanic lithosphere subducts, it adds water to and thereby weakens the upper mantle. It lowers the melting temperature, and decreases its strength. This may be the principal cause of the fragmentation of the oceanic lithosphere in the western Pacific.

ZAGROS AND MAKRAN MOUNTAINS

The Zagros are a system of folded mountains in western and southern Iran, extending about 1,100 miles (177 km) from the Turkish-Russian-Iranian border, to Zendam fault north of the Strait of Hormuz. The Makran Mountains extend east from the Zagros, through the Baluchistan region of Iran, Pakistan, and Afghanistan. The mountains form the southern and western borders of the Iranian Plateau and Dasgt-e Kavir and Lut Deserts. The northwestern Zagros are forested and snow-capped, and include many volcanic cones, whereas the central Zagros are characterized by many cylindrical folded ridges and interridge basins. The southwest Zagros and Makran ranges are characterized by more subdued topography with bare rock, sand dunes, and lowland salt marshes. Many major oil fields are located in the western foothills of the central Zagros, where many salt domes have punctured through overlying strata creating many oil traps.

Southwestern central Iran has been an active continental margin since the Mesozoic, with at least three main phases of magmatic activity related to



Tectonic map of parts of Iran, Afghanistan, and Arabia showing the Zagros, Makran, and Oman Mountains subduction of Tethyan oceanic crust beneath the mountain ranges. Late Cretaceous magmatism in the Makran formed above subducting oceanic crust related to the Oman ophiolite preserved on the Arabian continental margin. In the late Eocene the axis of active magmatism shifted inland away from the Mesozoic magmatic belt, but then shifted back during the Oligocene-Miocene. The Oligocene-Miocene magmas are also related to subduction of oceanic crust, suggesting that the Arabian-Iranian collision did not begin until the Miocene. Most of the southern Zagros consists of folded continental margin sediments of the Arabian platform, deformed since the Miocene and mostly since the Pliocene. In contrast, the Makran is an oceanic accretionary wedge consisting of folded Cretaceous to Eocene flysch- and ribbon-chert–bearing mélange resting above the subducting oceanic crust of the Gulf of Oman. A large ophiolitic sheet is thrust over the ophiolitic mélange and flysch and is part of a large ophiolitic belt that stretches the length of the Makran-Zagros ranges, falling between the Cenozoic volcanics and accretionary wedge/folded platform rocks of the Makran and Zagros. The main differences between the Zagros and the Makran exist because continent/continent collision has begun in the Zagros, but has not yet begun in the Makran.

Iran is seismically active, as shown by the devastating magnitude 6.7 earthquake that destroyed the ancient walled fortress city of Bam on December 26, 2003, killing an estimated 50,000 people. The Zagros belt is extremely active, where thrust-style earthquakes occur beneath a relatively ductile layer of folded sedimentary rocks on the surface. The Makran accretionary wedge is also seismically active, especially along the boundary where the subduction zone and upper-plate accretionary wedge meet. The boundary between the Makran and Zagros is a structurally complex region where many strike-slip faults, including the Zendan fault and related structures, rupture to the surface. The Bam earthquake was a strike-slip earthquake, related to this system of structures. The central Iranian plateau is also seismically active, and experiences large-magnitude earthquakes that rupture to the surface.

ENVIRONMENTAL DISASTER OF THE ARAL SEA

The Aral Sea is a large inland sea in southwestern Kazahkstan and northwest Uzbekistan, east of the Caspian Sea. The Aral Sea is fed by the Syr Darya and Amu Darya Rivers, which flow from the Hindu Kush and Tien Shan Mountains to the south, and is very shallow, attaining a maximum depth of only 220 feet (70 m). In the latter half of the 20th century the Soviet government diverted much of the water from the Syr Darya and Amu Darya for irrigation, and this has had dramatic effects on the inland sea. In the 1970s the Aral was the world's fourth-largest lake, covering 26,569 square miles (68,000 km^2). It has an average depth of 52.5 feet (16 m), and was the source of about 45,000 tons of carp, perch, and pike fish caught each year. Since the diversion of the rivers, the Aral has shrunk dramatically, retreating more than 31 miles (50 km) from its previous shore, lowering the average depth to fewer than 30 feet (9 m), reducing its area to fewer than 15,376 square miles (40,000 km^2), and destroying the fishing industry in the entire region. Furthermore, since the lake bottom has been exposed, winds have been blowing the salts from the evaporated water around the region, destroying local farming. The loss of evaporation from the sea has even changed the local climate, reducing rainfall and increasing temperatures, all of which exacerbate the problems in the region. Disease and famine have followed, devastating the entire Central Asian region.

See also ARABIAN GEOLOGY; ATMOSPHERE; CONVERGENT PLATE MARGIN PROCESSES; CRATON; FLOOD; INDIAN GEOLOGY; PRECAMBRIAN; RUSSIAN GEOLOGY; SUPERCONTINENT CYCLES.

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asteroid Asteroids and comets are space objects that orbit the Sun. When these objects enter the Earth's atmosphere, they may make a streak of light known as a meteor, and if they are not burned up in the atmosphere, the remaining rocky or metallic body is known as a meteorite. By definition, asteroids are a class of minor planets that have a diameter fewer than 620 miles (1,000 km), whereas planets are roughly spherical objects that orbit the Sun and have a diameter greater than 620 miles (1,000 km). Comets are partly icy bodies that may have rocky cores and typically orbit the Sun in highly elliptical paths. Most streaks of light known as meteors are produced by microscopic or dust-sized particles entering the atmosphere. Larger objects falling to Earth from space make a larger streak of light, known as a fireball, as they burn up on entry through the atmosphere.

Earth formed through the accretion of many asteroids about 4.5 billion years ago. As the solar system was condensing from a spinning disk of gas and dust particles, these particles began to collide, sometimes sticking to other particles. Gradually the particles became bigger and bigger until they were large rocky and metallic asteroids, which collided with each other until some became so large that they began collecting other asteroids through their gravitational attraction. These protoplanets swept their orbits clear of other asteroids and gradually grew larger in the process. Many of the protoplanets grew large enough to start melting internally, producing layered planetary bodies with dense cores and lighter crusts. At this late stage many protoplanets, including Earth, experienced collisions with other large protoplanets, causing catastrophic melting and fragmentation of the earliest planetary crusts. As this late-stage accretion period ended, Earth went through a period called the late bombardment, when many smaller meteorites were still falling to Earth, causing local disruption of the crust. Since then the number of meteorites that hit Earth has been gradually decreasing, but in the rare events when medium or large objects from space hit Earth, the results can be devastating.

Meteorites are rocky objects from space that strike Earth. When meteorites pass through Earth's atmosphere, they get heated and their surfaces become ionized, causing them to glow brightly, forming a streak moving across the atmosphere known as a shooting star or fireball. If the meteorite is large enough, it may not burn up in the atmosphere and will then strike Earth. Small meteorites may just crash on the surface, but the rare, large object can excavate a large impact crater, or do worse damage. At certain times of the year Earth passes through parts of the solar system that are rich in meteorites, and the night skies become filled with shooting stars and fireballs, sometimes as frequent as several per minute. Examples of these high-frequency meteorite encounters, known as meteor showers, include the Perseid showers that appear around August 11 and the Leonid showers that appear about November 14.

A large body of evidence now suggests that an impact with a space object, probably a meteorite, caused the extinction of the dinosaurs and 65 percent of all the other species on the planet at the end of the Cretaceous Period 66 million years ago. The meteor impact crater is apparently preserved at Chicxulub on Mexico's Yucatán Peninsula, and the impact occurred at a time when the world's biosphere was already stressed, probably by massive amounts of volcanism, global atmospheric change, and sea-level fall. The volcanic fields that were being laid down for a few million years before the mass extinction and death of the dinosaurs are preserved as vast lava plains in western India known as the Deccan traps. Impacts and massive volcanism can both dramatically change the global climate on scales that far exceed the changes witnessed in the past few thousands of years, or in the past hundred years as a result of human activities such as burning fossil fuels. These changes have dramatic influences on evolution and the extinction of species, and current research suggests that impacts and volcanism have been responsible for most of the great extinctions of geological time.

Impacts cause earthquakes of unimaginable magnitude, thousands of times stronger than any ever observed on Earth by humans. If a meteorite lands in the ocean, it can form giant tsunamis hundreds if not thousands of feet (m) tall that sweep across ocean basins in minutes, and run up hundreds of miles (km) onto the continents. Impacts kick up tremendous amounts of dust and hot flaming gases that scorch the atmosphere and fill it with Sun-blocking dust clouds for years. Global fires burn most organic matter in a global fireball, and these fires are followed by a period of dark deep freeze, caused by the atmospheric dust blocking out warming sunlight. This may be followed rapidly by a warm period after the dust settles, caused by the extra CO_2 released in the atmosphere by the impact. These severe and rapid changes in atmospheric and oceanic temperature and chemistry kill off many of the remaining life-forms in the oceans.

Collisions of asteroids with each other in the early history of the solar system led to the formation of planets but left many asteroids and other debris scattered at different places in the solar system. After the initial periods of accretion of the planets, the bombardment of the planets by asteroids decreased, but some bodies still fall to the planets as meteorites. Most are small and burn up before they hit the surface, but others have inflicted tremendous disruption on the planet. However, collisions of comets with Earth are largely responsible for bringing the lighter, volatile elements, including those that make up the planet's air and oceans, to Earth. It is also probable that asteroids or comets brought primitive organic molecules or even life to the planet.

ORBITS OF ASTEROIDS AND COMPOSITIONAL CLASSIFICATION OF METEORITES

Understanding of the composition of meteorites and asteroids has evolved with time. Early studies relied on meteorites, the bodies that had fallen to Earth, since no space travel or observations in space were possible during the previous centuries. Recently space missions to asteroids and remote sensing have enabled observations of asteroids in space to be integrated with the data from samples taken from meteorites collected on Earth.

The ice content in asteroids generally increases as the distance of their orbits from the Sun increases. Geologists classify meteorites collected on Earth according to the composition (reflected in the types of minerals present) and how much they have been metamorphosed, or changed by events that have subjected the meteorites to higher temperatures and pressures. Many meteorites were part of planetesimals (small planets) that had formed iron-rich cores, and then were probably destroyed in a catastrophic collision with another large asteroid early in the history of the solar system, spreading the asteroid debris of both planetesimals across the solar system. Other asteroids, comets, and meteorites appear not to have ever been part of larger planets, and may represent some of the primordial matter from the solar nebula from which the solar system formed.

Meteorites are classified on the basis of their composition and structure. The aim of such a classification scheme is to group together all the known bodies that may share a common parent body, whether it was a large asteroid, comet, planet, or moon. This is achieved by placing known asteroids into groups and subgroups based on their important mineralogical, physical, chemical, and isotopic properties.

Meteorites are made from material similar to that which makes up the Earth, including common silicate minerals, plus iron and nickel metals. Some meteorites also contain small lumps of material called chondrules, which represent melt droplets that formed before the meteorite fragments were accreted to asteroids, and thus represent some of the oldest material in the solar system. Some meteorites also contain presolar grains, often comprising tiny carbon crystals in the form of diamonds.

Traditional classification schemes for meteorites broke them into three main groups based on composition. These groups include stony meteorites composed mosty of rocky material, iron meteorites composed mostly of metallic material, and mixtures called stony-iron meteorites. These groups were then divided into subgroups; for instance, the stony meteorites were divided into chondrites and achrondrites according to whether or not they contained chondrules. The iron meteorites were divided into textural groups including structures such as octahedrites, hexahedrites, and ataxites. More recently these textures have not been used for classification but only for descriptive purposes, and the iron meteorites are further divided according to their chemistry. Stony-iron meteorites were divided into pallasites and mesosiderites.

More modern schemes use a simpler classification, in which meteorites are classified as either chondrites or nonchondrites. The nonchrondrites are divided into primitive and differentiated types. The differentiated nonchondrites have three groups, including the achondrites, stony-irons, and irons.

Recognizing meteorites on Earth is difficult since they have similar minerals to many Earth rocks. Many meteorites develop a fused crust on their surface from the heat during entry through Earth's atmosphere. Most of the meteorites from Earth used for classifications have been collected from Antarctica, where the only place for rocks on the ice fields to come from is space. Most, about 85 percent of all meteorites falling on Earth, are chondrites, thought to represent largely primitive solar material. For the nonchrondrites, many classifications and descriptions are aimed at determining whether they come from larger parent bodies that broke up during early impacts, and if so, what the characteristics of this parent body may have been.

Chondrites

Chondrites are meteorites that have chemical compositions similar to that of the Sun. Since the Sun makes up about 99 percent of the mass of the solar system, it is assumed that the composition of the Sun represents the average composition for the entire solar system, and that this average composition resembles the original composition of the solar system when it was formed. Therefore since chondrites and the Sun have similar compositions, chondrites are thought to have very primitive compositions that are close to the average starting material that formed the solar system.

Chondritic meteorites contain small round nodules called chondrules that consist of a mixture of crystals and glass. Most interpretations for the origin of chondrules suggest that they represent small droplets of liquid that condensed during the earliest stages of the formation of the solar system, before they were incorporated into the meteorites. Chondrules that have been dated yield isotopic ages of 4.568 billion years, the time that the solar system began to condense from the solar nebula. Thus, chondrules represent small remnants of the earliest solar system material. Other chondritic meteorites, such as the famous Allende meteorite, that have been dated also give ages of 4.566 billion years, similar to that obtained from the chondrites.

Many experiments have been done on chondrules to determine their exact components and the conditions in which they formed since they are interpreted to have formed during the early stages of the formation of the solar system. Knowing the conditions of their formation yields information about the conditions in the early solar system and solar nebula. Most experiments show that the chondrules formed at temperatures of at least 2,700°F (1,500°C) and that the chondrules cooled rapidly. Some chondrules contain unusual minerals. One group of these contains a suite of very high-temperature minerals and is called calcium-aluminum inclusions (CAIs), typically exhibiting textures like concentric skins of an onion. Experiments on the temperature of formation of these CAIs indicate that they formed at temperatures of at least 3,100°F (1,700°C) and underwent slow cooling. From these extraordinarily high temperatures scientists infer that these CAIs represent the oldest parts of the oldest fragments of the early solar system.

Most chondritic meteorites consist of mixtures of chondrules and the minerals olivine and pyroxene, and show little evidence of being heated or metamorphosed since they formed. Some, however, show textures like partial melting that indicate they were heated to temperatures of up to 1,800°F (1,000°C) after they formed. Still others are cut by veins that have minerals with water in their structures such as carbonates, sulfates, and magnetite. Thus water existed in the asteroid belt in the early solar system. The range in the amount of heating of chondrites likely reflects that they were incorporated into a larger body, with the higher temperature heating happening deeper inside this now-destroyed asteroid or protoplanetary body.

Isotopic dating techniques have shown that most chondritic meteorites cooled within 60 million years of the time of the formation of the solar system. Some time after that, impacts in the asteroid belt between the orbits of Mars and Jupiter broke the larger protoplanets or asteroid parent bodies into smaller pieces now preserved as the asteroid belt. Some chondrites are composed of strongly fragmented rock called breccia, produced by these early collisions in the asteroid belt. Calculations of the pressures needed to produce these breccias indicate that the pressures reached 75 giga Pascals, or the equivalent of 750,000 times the atmospheric pressure on Earth.

Chondritic meteorites are divided into a number of classes with similar compositions and textures, thought to represent formation in similar parts of the solar system. These in turn are divided into groups thought to represent fragments of the same parent body.

The main classes of chondrites include the ordinary chondrites, carbonaceous chondrites, and enstatite chondrites. Some classifications add further subdivisions based on the type of alteration or metamorphism, such as alteration by water, or metamorphism by late heating. Ordinary chondrites are thought to have formed in parent bodies that were 100–120 miles (165–200 km) in diameter. Carbonaceous chondrites contain organic material such as hydrocarbons in rings and chains, and amino acids. Even though these organic molecules can serve as building blocks of life, no life has been found on any meteorites unless they were contaminated on Earth. Enstatite chondrites contain small sulfide minerals that indicate very rapid cooling, suggesting that the original material came from deep in a larger body that was broken apart by strong impacts, and the deep material cooled quickly in space after the violent collisions. The enstatite chondrites typically have impact breccias in their structures.

Achondrites

Achondrite meteorites resemble typical igneous rocks found on Earth. They formed by crystallizing from a

Computer artwork of main asteroid belt of the solar system (not to scale), between orbits of Mars and Jupiter *(Mark Garlick/Photo Researchers, Inc.)*

silicate magma and are remnants of larger bodies in the solar system that were large enough to undergo differentiation and internal melting. These meteorites do not contain chondrules or remnant pieces of the early solar system since they underwent melting and recrystallization.

Some achondrites have been shown to have origins on the Earth's moon and on Mars. They formed by crystallization from magma on these bodies, and were ejected from the gravitational fields of these bodies during large-impact events. The debris from these impacts then floated in space until being captured by the gravitational field of Earth, where they fell as meteorites. These meteorites are named for the places they have fallen on Earth, and include shergottites (Shergotty [Shergahti], India), nakhlites (El Nakhla, Egypt), and chassignites (Chassigny, France) (collectively named SNC meteorites after these three falls). SNC achondrites have ages between 150 million and 1.3 billion years, billions of years younger than other meteorites and the age of the solar system. These ages mean that the SNC meteorites must have come from a large planet that was able to remain hot and sustain magma for a considerable time after formation at 4.56 billion years ago. Chemical analysis of the SNC meteorites revealed that most match the bulk chemistry of Mars, confirming the link. Analysis of the damage done to the surface of these meteorites by cosmic rays as they were in space has yielded estimates for the time of transit from the ejection during impact on Mars to the landing on Earth at fewer than 2 million years. Thus most of the SNC meteorites originated from meteorite impacts on Mars in the past 1–20 million years. An estimated billion tons of material has landed on Earth that was originally ejected by meteorite impact on Mars. A smaller number of SNC meteorites have been shown to come from the Earth's moon.

Other achondrites formed on other bodies that have been destroyed by giant impacts. For example, the howardites, eucrites, and diogenites are thought to have formed in one body, the largest remnant of which is the asteroid 4 Vesta, currently orbiting the Sun in the asteroid belt. The eucrites and diogenites represent basaltic magma produced on this early protoplanet and destroyed by a large impact at 4.4 billion years ago, within a hundred million years of the formation of the solar system. Eucrites are basalts that contain the minerals clinopyroxene and plagioclase, diogenites contain orthopyroxene that formed layers of dense crystals called cumulates, and howardites are breccias of these rocks that formed during the giant impact that destroyed the parent achondrite body.

A number of unusual achondrites have no known parent bodies. These include the acapulcoites, angrites, brachinites, lodranites, and urelites. Some of these are relatively primitive—for instance, the urelites formed early in the solar system evolution, were heated inside a large parent body and crystallized at 2,300°F (1,250°C), were destroyed in a massive impact, then cooled at 50°F (10°C) per hour in the cold vacuum of space. One arubite shows a remarkably fast cooling rate of 1,800°F (980°C) per hour, probably coming from deep within the parent body then being suddenly frozen in space. Brachinites show some of the earliest igneous activity known from any asteroid body, showing the earliest time at which planets may have begun accreting in the early solar system. The crystallized magmas from these bodies have given ages of 4.564 billion years, meaning that the accretion of planetesimals to a size that could partially melt from the solar nebula happened within 5 million years.

Iron Meteorites

Iron meteorites consist of iron, 5–20 percent nickel, and some minor metals, and they contain almost no silicate minerals. They are thought to represent the differentiated cores of large planetesimals or protoplanets that formed in the early solar system in the asteroid belt, grew large enough to melt partially and differentiate into core and mantle and crust, then were broken apart by large impacts exposing the core material to outer space. Iron meteorites therefore represent valuable samples of the cores of planetary bodies.

Iron meteorites are famous for exhibiting a crisscross texture known as the Widmannstatten texture best shown in polished metallic surfaces. This is produced by intergrown blades of iron and nickel minerals; the size of the blades is related to the cooling rate of the minerals. The slower the cooling, the larger the crystals grow, so it is possible to calculate the cooling rate of the early planetesimals using the Widmannstatten texture, and from that infer the size of the early planetesimals. A range of different cooling rates and sizes has been determined, from 210°F (100°C) per hour in a body of fewer than 48 miles (80 km) in diameter, to cooling at 9°F (5°C) per year in a body up to 210 miles (340 km) in diameter. Just like the chondrites, the iron meteorites are estimated to have formed into the parent bodies or planetesimals within 5 million years of the formation of the solar system. Additional analysis of the cosmic ray interaction of the surfaces of the iron meteorites can tell the amount of time that they have been exposed and traveling through space. In this case the exposure age, dating from the time of breakup of the parent body to the time the meteorites fell to Earth, is remarkably different from other meteorites. The iron meteorite parent bodies apparently broke up by impacts only between 200 million and 1 billion years ago, and thus had survived as large bodies in the asteroid belt for 3.5 to 4.5 billion years.

Iron meteorites are divided into groups on the basis of texture, how the iron and nickel minerals are intergrown, and the sizes of the crystals. The main groups include octahedrites, hexahedrites, and ataxites. They are further divided into a large number of classes based on their chemical characteristics, which indicate that they formed in at least several different parent bodies.

Stony-Iron Meteorites

As the name implies, stony-iron meteorites consist of mixtures of metal and silicate (rocky) components, resembling a cross between achondrites and iron meteorites. They are thought to come from the part of a planetesimal or parent body near the boundary of the core and mantle, incorporating parts of each in the meteorite.

Stony-iron meteorites are classified into pallasites and mesosiderites. Pallasites contain a mixture of Widmannstatten-textured iron phases and large yellow to green olivine crystals, formed along the core-mantle boundary of the parent body. Mesosiderites consist of silicate minerals with inclusions of iron that melted in the core of the parent body. Mesosiderites are puzzling, because the silicate phases are magmatic rocks that formed near the surface of the parent body, and the iron phases are melts from the core of the body. Ages for mesosiderites range from 4.4 to 4.56 billion years, so they formed early in the history of the solar system. Some models suggest that they are breccias from bodies that only partially differentiated in the planetsimal forming stages of the solar system. These bodies broke up by impact by 4.2 billion years ago, then apparently were reassembled by gravity within 10–170 million years. The parent body for the mesosiderites was between 120 and 240 miles (200–400 km) in diameter.

ORBITS AND LOCATION OF ASTEROIDS IN THE SOLAR SYSTEM

Asteroids have been named and numbered in the order they were discovered, since the first discovery of asteroid 1 Ceres in 1801. Most of the large asteroids are located in the main asteroid belt between Mars and Jupiter and are thought to have originated by numerous collisions between about 50 large planetesimals in the early history of the solar system. In this belt the vast number of relatively large bodies meant that there were many mutual collisions, and they never coalesced into a single large body like the other planets. There are 33 known asteroids with diameters larger than 120 miles (200 km), and 1,200 known with diameters larger than 19 miles (30 km). The largest is 1 Ceres (590 miles, or 960 km), and the other large asteroids in this belt include 2 Pallas (350 miles, 570 km), 4 Vesta (326 miles, 525 km), 10 Hygiea (279 miles, 450 km), 15 Eunomia (169 miles, 272 km), and Juno (150 miles, 240 km).

Like planets, asteroids orbit the Sun and rotate on their axes, although many asteroids have more of a tumbling motion than the spinning typical of planets. Many asteroids have unusual shapes, and it is not unusual for asteroids to resemble familiar objects, like giant dog bones (216 Kleopatra, 135 miles, 217 km long) tumbling through space. Typical periods of rotation (corresponding to the length of a day) range from 3 hours to several Earth days, with most falling around periods of 9 hours. Many asteroids are really collections of blocks of rubble all rotating in the same place. These are thought to be asteroids that were once single solid masses, but were strongly fractured and broke apart while in orbit.

Inner Solar System Asteroids

Relatively few asteroids orbit inside the orbit of Jupiter, since the numerous planets and proximity to the Sun in this region exert many forces that cause the orbits of bodies to become unstable. Most asteroids that end up orbiting in the inner solar system (between Jupiter and the Sun) are deflected there by collisions in the other asteroid belts, and have short lifetimes before they collide with a planet, are pulled into the Sun, or are deflected back to outer space.

Despite these forces, a couple of places in the inner solar system exist where gravitational physics lets asteroids have stable orbits. Called resonances, these stable orbits are an effect of the gravity and different orbital periods of the larger planets in the inner solar system. Some locations (the resonances) are at stable locations for bodies that orbit at specific rates relative to the larger planets. The largest planet, Jupiter, forms several resonances within which many asteroids orbits, generally known as Jovian asteroids. These include the Trojans, which have an orbital period equal to Jupiter's; another group known as the Hildas, which orbit three times for every two orbits of Jupiter; and the Thule asteroids, which orbit four times for every three orbits of Jupiter. Just as the resonances represent stable places for asteroids to orbit, the gravitational forces of large planets such as Jupiter cause some places to be particularly unstable for asteroids. These places devoid of asteroids are known as Kirkwood Gaps (after their discoverer, Daniel Kirkwood, who first described them in 1886).

Gravitational physics results in additional locations that represent stable orbits for asteroids in the inner solar system. These stable orbits were first described by the French mathematician Joseph-Louis Lagrange in the late 18th century. Lagrange showed that for a two-body system (e.g., the Sun and a large planet like Jupiter) there are five orbital positions inside the orbit of the planet where the gravitational pull of the two large bodies is equal to the centripetal force acting on other bodies between them, and that the two forces cancel each other and make these stable orbits. Three of the five Lagrange orbits turn out to be unstable over long geological periods, but two yield long-term stable orbits for asteroids. These two so-called Lagrange points turn out to be in the orbit of the planet, located 60 degrees ahead and 60 degrees behind the position of the planet. Asteroids in the solar system located in these points are called Trojans, and many asteroids in the inner solar system fall into this category. Trojans exist for the Sun-Jupiter gravitational system, for the Sun-Mars system, and for many other planets in the solar system. The most abundant Trojans orbit in synchroneity with Jupiter, then with Mars, on either side of the main asteroid belt. The Sun-Earth system has dense concentrations of dust at the Trojan points but no know asteroids.

Gravitational physics predicts that there are two main stable regions in the inner solar system where many asteroids may exist with stable orbits for long periods of time. The first location is inside the orbit of Mercury, but no asteroids have yet been identified in this region. Asteroids that may be in this region are named Vulcan objects, but have proven difficult to observe because of their proximity to the Sun. The second large stable region for asteroids in the inner solar system is known as the main belt, divided into several subbelts, between the orbits of Mars and Jupiter.

Main Asteroid Belt

By far the largest number of asteroids in the inner solar system are located in the main asteroid belt between the orbits of Mars and Jupiter. There are estimated to be between 1.1 and 2 million asteroids in this belt with diameters greater than half a mile (1 km), comprising about 95 percent of the known asteroids. There are probably billions of objects in this belt with diameters of less than half a mile (1 km). Despite the large number of objects in the main asteroid belt, the total mass of all asteroids in this belt is less than one-tenth of 1 percent of the mass of the Earth, and represents a mass less than the Earth's moon.

In 1993 the *Galileo* spacecraft flew about 1,500 miles (2,400 km) from asteroid Ida at a relative velocity of 28,000 mph (12.4 km/sec), in the second encounter of an asteroid by a spacecraft. At the time of nearest pass, the asteroid and spacecraft were 274 million miles (441 million km) from the Sun. Ida is about 32 miles (52 km) in length, more than twice as large as Gaspra, the first asteroid observed by *Galileo* in October 1991. Ida is an irregularly shaped asteroid placed by scientists in the S class (believed to be like stony or stony-iron meteorites). It is a member of the Koronis family, presumed fragments left from the breakup of a precursor asteroid in a catastrophic collision. It has numerous craters, including many degraded craters larger than any seen on Gaspra. The extensive cratering dispels theories about Ida's surface being geologically youthful.

The main asteroid belt is located between 1.7 to 4 astronomical units (A.U., or the distance from the Sun to Earth) from the Sun, in an unusually large gap, between the planets of Mars and Jupiter. Early models for this gap and the asteroids suggested that perhaps there was once a planet in this gap that was destroyed by a tremendous impact that resulted in the formation of the asteroids. Some of the asteroids obviously come from once-larger objects, since their metallic material comes from a differentiated core of a planetlike body, and these differentiated cores need a planet of at least a few hundred miles (few hundred km) to form. It is now clear, however, that the huge gravitational forces from Jupiter are so large that they would have prevented a large planet from ever forming in that gap. Models for most of these asteroids suggest that some formed a number of several-hundred-mile (km) diameter planetesimals, but that none ever reached true planet size. These planetesimals then repeatedly crashed into each other, forming the numerous odd-shaped fragments in the belts. Other asteroids in the main asteroid belt have compositions that show that they were never part of larger bodies, and that they represent material that is "left over" from the solar nebula, still floating freely in space. One of the classes of asteroids, known as carbonaceous chondrites, shows unmetamorphosed (never heated or put under high pressure) minerals, demonstrating that they were never deep in a planetary interior and never located next to the Sun. The compositions of the main-belt asteroids show that they formed in about the same region in which they are located with respect to distance from the Sun.

The main asteroid belt contains several belts of asteroids, and these show variations with distance from the Sun, thought to represent variations in the original solar nebula and in the different parent bodies that broke up during formation of the solar system. One of the main differences is that asteroids inside 2.5 A.U. have no water, whereas beyond 2.5 A.U. the asteroids have water, the amount increasing with distance from the Sun. Not coincidentally, the planets inside the asteroid belt are rocky, whereas those outside the belt are gaseous and icy.

The innermost group of asteroids in the main belt, just beyond the orbit of Mars at 1.52 A.U., are the Hungaria objects, orbiting between 1.78 and 2.0 A.U. These are followed outward by the Flora family between 2.1 and 2.3 A.U., then the main part of the main asteroid belt between 2.3 and 3.25 A.U. The Koronis asteroids are located in this main section of the main belt, including more than 200 identified large bodies orbiting around 3 A.U. A gap lies outward of the Koronis asteroids, then the Cybele family asteroids orbit the Sun at a distance of 3.5 A.U., with properties suggesting they originated from a single large planetsimal destroyed early in the history of the solar system. The outermost part of the main asteroid belt is occupied by the Hilda asteroids, orbiting in a resonance from Jupiter at 3.9 to 4.2 A.U. Beyond the Hilda family is a gap, followed by the orbit of Jupiter and its Trojans.

Aten, Apollo, and Amor-Class Asteroids

In addition to the stable belts numerous asteroids in the inner solar system have unstable orbits, and these bodies present the greatest threat to Earth and its inhabitants. The orbits of some of these asteroids cross the paths of other planets, including Earth, and pose an even greater risk of impact. These asteroids are classified according to their distance from the Sun.

Aten asteroids orbit less than one A.U. and an orbital period of less than one year, and some of these cross Earth's orbit. Many of the more than 220 known Aten objects are being tracked, as they pose a high risk of impact with Earth. Apollo asteroids are similar to Atens in that they cross Earth's orbit, except they have periods longer than one year. Of the more than 1,300 known Apollo asteroids, the largest is 1685 Toto, which is 7.5 miles (12 km) across. Collision of this object with Earth would be cataclysmic. More than 13 Apollo asteroids have diameters greater than 3 miles (5 km), all of which are larger than the asteroid that hit Earth at the end of the Cretaceous, killing the dinosaurs and causing a mass extinction event. Another class of inner planet–crossing asteroids are the Amors, which orbit between Earth and Mars but do not cross Earth's orbit. There are more than 1,200 known Amor objects, and the moons of Mars (Deimos and Phobos) may be Amors that were gravitationally captured by Mars.

The asteroid deemed the most threatening to Earth (among known objects) is 4179 Toutatis. This asteroid measures a mile (1.6 km) across and orbits in a plane only one-half a degree different from Earth's. Because the asteroid that hit Chicxulub and killed the dinosaurs was only 6 miles (10 km) across, the devastation potential of a collision of Earth with Toutatis is colossal. The possibility of a collision is not that remote—on September 29, 2004, Toutatis passed by Earth at only four times the distance to the Moon. The next-largest object in nearly coplanar orbits with Earth are less than 0.6 miles (1 km) in diameter, but a collision with these would also produce an impact crater greater than 15 miles (25 km) across. Impact statistics predict that objects this size should still be hitting Earth three times per million years.

Outer Solar System Asteroids

The outer solar system, beyond the orbit of Jupiter, is awash in asteroids, most of which are icy compared with the rocky and metallic bodies of the inner solar system. In addition to the Trojans around Jupiter, a group of about 13,000 asteroids with highly eccentric and inclined orbits cross the path of Jupiter, in positions that cause relatively frequent collisions and deflections of the asteroids into the inner solar system. Asteroids whose orbits are inside the orbit of a planet generally do not hit that planet, but only hit planets closer to the Sun than its orbit. This is an artifact of the great gravitational attraction of the Sun, constantly pulling these objects closer in toward the center of the solar system.

Centaurs, a group of asteroids with highly eccentric orbits that extend beyond yet cross the orbits of Jupiter and Saturn, can thus potentially collide with these planets. Many of these are large bodies thought to have been deflected inward from the Kuiper belt, into unstable orbits that have them on an eventual collision course with the giant planets, or to be flung into the inner solar system. Coming from so far out in the solar system, Centaurs are icy bodies. One Centaur, Chiron, is about 50 miles (85 km) in diameter, is classified as a minor planet, and exhibits a cometary tail when at its perihelion but not along other parts of its orbit. Chiron therefore is classified as both an asteroid and a comet.

Trans-Neptunian objects are a class of asteroid that orbit beyond the orbit of Neptune at 30 A.U., and beyond into the Kuiper belt, extending from 30 to 49 A.U. Beyond the Kuiper belt is a gap of about 11 A.U. containing relatively few asteroids before the beginning of the Oort Cloud. The total number of objects in this belt is unknown but undoubtedly large, because many are being discovered as the ability to detect objects at this distance increases. More than a thousand Trans-Neptunian objects are currently documented.

Kuiper Belt

The Kuiper belt contains many rocky bodies and is thought to be the origin of many short-period comets. Few of the known Kuiper belt objects have been shown to have frozen water, however, but may have ices of other compositions. The total mass of asteroids in the Kuiper belt is estimated at about 20 percent of Earth's mass, about 100 times as much as the mass of the main asteroid belt.

Formerly classified as a planet, Pluto, and its moon, Charon, are Kuiper belt objects. Pluto is one of the larger Kuiper belt objects, but its size is not anomalous for the belt—there are thought to be thousands of Kuiper belt objects with diameters greater than 600 miles (1,000 km), 70,000 asteroids or comets with diameters greater than 60 miles (1,000 km) and half a million objects with diameters greater than 30 miles (50 km). Saturn's moon Phoebe is an icy captured asteroid that was deflected inward from the Kuiper belt and gravitationally captured by Saturn. Its surface shows a mixture of dusty rock debris and ice.

Oort Cloud

The Oort Cloud is a roughly spherical region containing many comets and other objects, extending from about 60 A.U. to beyond 50,000 A.U., or about 1,000 times the distance from the Sun to Pluto, or about one light year. This distance of the outer edge of the solar system is also about one quarter of the way to the closest star neighbor, Proxima Centauri. The Oort Cloud is thought to be the source for long-period comets and Halley-type comets that enter the inner solar system. It contains rocky as well as icy bodies.

The Oort Cloud can be divided into two main segments including the inner, doughnut-shaped segment from 50 to 20,000 A.U., and the outer spherical shell extending from 20,000 to at least 50,000 A.U. Some estimates place the outer limit of the Oort Cloud at 125,000 A.U. The inner part of the Oort Cloud is also known as the Hills Cloud. It is thought to be the source of Halley-type comets, whereas the outer Oort Cloud is the source of the long-period comets that visit the inner solar system. The Hills, or inner Oort Cloud, contains much more material than the outer Oort Cloud, yet the outer cloud contains trillions of comets and bodies larger than 0.8 mile (1.3 km) across, spaced tens of millions of miles (km) apart. The total mass of the outer Oort Cloud is estimated to be several Earth masses.

COMPOSITION AND ORIGIN OF ASTEROIDS, METEORITES, AND COMETS

The asteroid belt is thought to have originated as a group of larger planetesimals that began to be formed within 5 million years of the formation of the solar system, and that soon afterward the planetesimals began to be broken apart by mutual collisions among them. Some collisions happened within a few tens to hundreds of millions of years after initial formation of the bodies; others have happened within the past 200 million years. Most of these collisions are induced by the gravitational forces between Jupiter and the Sun.

The composition of asteroids is determined through remote sensing methods, typically using reflection spectra from the surfaces of asteroids. Presently no samples have been returned from exploration missions to asteroids, so it is difficult to correlate directly their composition with meteorites. The remote sensing studies of asteroids reveal that they have a diverse range of compositions and closely match the range of meteorite compositions found on Earth. In this way some meteorites have been matched to remnants of their parent bodies in the asteroid belt. For instance, asteroid 4 Vesta has the same composition as and is thought to be the largest remnant of the parent body for the howardite, eucrite, and diogenite classes of achondrites.

The composition of asteroids changes gradually with distance from the Sun. The asteroids closest to Mars are classified as S-type silicate bodies and resemble ordinary chondrites. These are followed outward by more abundant B- and C-types, containing some water-rich minerals, and appear to be carbonaceous chondrites. D- and P-types rise in abundance outward, but these do not have any known correlatives in meteorites that have fallen to Earth. These dark objects appear rich in organic material.

The outer solar system asteroids, including those in the Oort Cloud, are thought to be the remnants of the original protoplanetary disc that the solar system formed from 4.6 to 4.5 billion years ago. Many of the objects in the Oort Cloud may have initially been closer to the Sun, but moved outward from gravitational perturbations by the outer planets. The current mass of the Oort Cloud, three to four Earth masses, is much less than the 50–100 Earth masses estimated to have been ejected from the solar system during its formation. It is possible that the outer edges of the Oort Cloud interact gravitationally with the outer edges of other Oort Clouds from nearby star systems, and that these gravitational interactions cause comets to be deflected from the cloud into orbits that send them into the inner solar system.

Bombardment of Earth by comets early in its history may have brought large quantities of water and organic molecules to the planet. In some models for the evolution of the early Earth, most of the volatiles initially on the planet were blown away by a strong solar wind associated with a T-Tauri phase of solar evolution, and the present-day atmosphere and oceans were brought to Earth by comets. Small microcomets continue to bombard Earth constantly, bringing a constant stream of water molecules to Earth from space.

SUMMARY

Modern classification schemes for the composition of asteroids and meteorites divide them into either chondrites or nonchondrites. The nonchondrites are divided into primitive and differentiated types. The differentiated nonchondrites have three groups, including the achondrites, stony-irons, and irons, based on the chemistry and texture of the meteorites and reflecting their origin. Chondrites have compositions similar to the Sun, and represent the average composition of the solar system, thought to be close to the original composition of the solar nebula. Many chondrites contain chondrules, which are small, originally liquid melt drops of the original material that condensed to form the solar system 4.6 billion years ago. Some chondrites contain calcium-aluminum inclusions, which may represent presolar system material. One class of chondrites, carbonaceous condrites, contain complex organic molecules. The variation in chondritic meteorites is thought to represent formation at different depth in a large, 100–120-mile (165–200-km) wide asteroid destroyed in a catastrophic collision early in the history of the solar system, dispersing the fragments across the solar system.

The nonchondrites are divided into primitive and differentiated types. The differentiated nonchondrites have three groups, including the achondrites, stony-irons, and irons. Achondrites are rocky silicate igneous rocks, whereas the irons consist of mixtures of iron and nickle. Stony-irons represent a transitional group. These meteorites are also thought to have formed in several parent bodies destroyed by collisions in what is now the asteroid belt, but these bodies were initially large enough (120–240 miles [200–400 km]) across that they were able to differentiate into crust, mantle, and core. The irons are from the core of these bodies, the achondrites from the mantle and crust, and the stony-irons from the transition zone. Some unusual achondrites have been shown to have been ejected from the Moon and Mars during impacts, eventually landing on Earth.

Most meteorites are thought to come from the asteroid belt, where 1–2 million asteroids with diameters greater than 0.6 miles (1 km) are orbiting the Sun between Mars and Jupiter. They may get pushed into Earth-crossing orbits after being deflected by collisions in the asteroid belt or by gravitational perturbations during complex orbital dynamics. Spectral measurements of some of the asteroids show that their compositions correlate with the meteorites sampled on Earth, and a crude gradation of compositions in the asteroid belt is thought to represent both the original distribution of different parent bodies that broke up during collisions and the initial compositional trends across the solar nebula. Asteroids closer to the Sun are rockier, with more silicates and metals, whereas those farther out have more ices of nitrogen, methane, and water.

Several different groups of asteroids have unstable orbits that cross the paths of the planets in the inner solar system. These objects represent grave dangers to life on Earth, as any impacts with large objects are likely to be catastrophic. These Earth and Mars orbit-crossing asteroids are classified according to their increasing distance from the Sun into Aten-, Apollo-, and Amor-class asteroids. Some of these asteroids are being tracked, to monitor the risk to life on Earth, since collisions of asteroids of this size are known to cause mass extinction events, such as the Cretaceous-Tertiary extinction that killed the dinosaurs. Major impacts occur on Earth about every 300,000 years.

The outer solar system also hosts belts of asteroids, and the number and mass of these objects pales in comparison with the amount of material in the inner solar system. There are many names for asteroids and other bodies orbiting in specific regions, but the bodies of most significance include the Trans-Neptunian objects that orbit beyond the orbit of Neptune at 30 A.U. and into the Kuiper belt, that extends to about 49 A.U. Beyond this there is a relatively empty gap before the beginning of the Oort Cloud at 60 A.U. Most objects in the Kuiper belt and the Oort Cloud consist of mixtures of rock and ice, and are the source region for comets. There are thought to be thousands of Kuiper belt objects with diameters greater than 600 miles (1,000 km), 70,000 asteroids or comets with diameters greater than 60 miles (1,000 km), and half a million objects with diameters greater than 30 miles (50 km).

The Oort Cloud represents the outer reaches of the solar system, and may actually extend into the Oort Cloud of the nearby star system, Proxima Centauri. There are thought to be trillions of comets in the Oort Cloud over 0.8 miles (1.3 km) in diameter, totally several Earth masses. The Oort Cloud is the source of long-period comets, with orbits longer than 200 years. Comets typically have a rocky core and emit jets of ices consisting of methane, water, and ammonia, and other ice compounds. Many comets are coated by a dark surface consisting of complex organic molecules, and these may be the source for much of the carbon and volatile elements on the Earth that presently make up much of the atmosphere and the oceans. Some scientists speculate that comets may be responsible for bringing the complex organic molecules to Earth that served as the building blocks for life.

See also ASTRONOMY; ASTROPHYSICS; COMET; METEOR, METEORITE; ORIGIN AND EVOLUTION OF THE EARTH AND SOLAR SYSTEM; SOLAR SYSTEM.

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asthenosphere The asthenosphere is the layer of the Earth's mantle between the lithosphere and the mesosphere. Its depth in the Earth ranges from about 155 miles (250 km) to zero miles below the midocean ridges, and 31 to 62 miles (50–100 km) below different parts of the continents and oceans. Some old continental cratons have deep roots that extend deeper into the asthenosphere. The asthenosphere is characterized by small amounts (1–10 percent) of partial melt that greatly reduces the strength of the layer and is thought to accommodate much of the movement of the plates and vertical isostatic motions. The name derives from the Greek for "weak sphere." S-wave seismic velocities clearly demarcate the asthenosphere and show a dramatic drop through the asthenosphere because of the partial melt present in this zone. Because of this the asthenosphere is also known as the low-velocity zone, and it shows the greatest attenuation, or weakening, of seismic waves anywhere in the Earth.

The asthenosphere is composed of the rock type peridotite, consisting primarily of the mineral olivine, with smaller amounts of the minerals orthopyroxene, clinopyroxene, and other accessory minerals including spinels such as chromite. The term *peridotite* is a general term for many narrowly defined ultramafic rock compositions including harzburgite, lherzolite, websterite, wehrlite, dunite, and pyroxenite. Peridotites are not common in the continental crust but are common in the lower cumulate section of ophiolites, in the mantle, and in continental layered intrusions and ultramafic dikes. Peridotites have unstable compositions under shallow crustal metamorphic conditions, and in the presence of shallow-surface hydrating weathering conditions, they commonly become altered to serpentinites through the addition of water to the mineral structures.

The asthenosphere is flowing in response to heat loss in the deep Earth, and geologists are currently debating the relative coupling between the flowing asthenosphere and the overlying lithosphere. In some models the convection in the asthenosphere exerts a considerable mantle drag force on the base of the lithosphere, and significantly influences plate motions. In other models the lithosphere and asthenosphere are thought to be largely uncoupled, with the driving forces for plate tectonics being more related to the balance between the gravitational ridge push force, slab pull force, slab drag force, transform resistance force, and subduction resistance force. There is also a current debate on the relationship between upper-mantle (asthenosphere) convection and convection in the mesosphere. Some models propose double or several layers of convection, whereas other models purport that the entire mantle is convecting as a single layer.

See also CONVECTION AND THE EARTH'S MANTLE; ENERGY IN THE EARTH SYSTEM; MANTLE; PLATE TECTONICS.

astronomy Astronomy is the study of celestial objects and phenomena that originate outside the Earth's atmosphere. The name is derived from the Greek words *astron* for star and *nomos* for law and includes the study of stars, planets, galaxies, comets, interstellar medium, the large-scale structure of the universe, and the natural laws that describe these features. Astronomy is also concerned with the chemistry and meteorology of stellar objects, the physics of motion, and the evolution of the universe through time.

A BRIEF HISTORY OF ASTRONOMY

Ancient cultures were fascinated with the heavens, and astronomy developed into one of the earliest sciences as these cultures formalized their studies of the night skies. Much of the work of these early astronomers focused on observations and predictions of the motions of objects visible to the naked eye, and some cultures erected large monuments that likely have astronomical significance. Early Jewish, Chinese, and other cultures established calendars based on observations and calculations of the Moon cycles, and these calendars became essential for determining seasons and knowing when to plant crops. By the year 1000 B.C.E. Chinese astronomers had calculated Earth's obliquity to the ecliptic, or the tilt of the planet's axis relative to the orbital plane about the Sun. Early astronomers included the study of astrology, celestial navigation, and time calculations such as making calendars in their field, but modern professional astronomy is equivalent to astrophysics, with branches of observational and theoretical astronomy.

A revolution in astronomy and science was marked by Polish astronomer Nicolaus Copernicus's (1473–1543) proposal in his book *De revolutionibus orbium coelestium* (On the revolutions of the heavenly spheres), where he proposed that the Earth is not the center of the universe as most previous scientists believed, but that the Earth and other planets orbit around the Sun. Astronomy changed from its classical period to its modern period with the invention of the telescope in the late 16th century. Some of the early Islamic scholars described the optics of lenses required for telescopes, but the first surviving instruments are from the Netherlands, invented by eye spectacle makers Hans Lippershey and Zacharias Janssen of Middleberg, and Jacob Matius of Alkaamar. In 1602 Galileo Galilei, a physicist from Tuscany, improved on these designs and produced a telescope that earned him the nickname father of modern observational astronomy. These designs were further improved by the English physicist Isaac Newton in 1668.

The German astronomer and natural philosopher Johannes Kepler (1571–1630) further described and refined the laws of planetary motion. Newton further explained these laws in his law of universal gravitation, still used as a general approximation for most gravity-driven processes. Albert Einstein's general theory of relativity more accurately describes gravity, but Newton's laws work for most applications. Further significant advances in astronomy came with the inventions of new technologies, including photography and the spectroscope. Spectroscopic observations of the Sun by Bavarian optician Joseph von Fraunhofer (1787–1826) showed about 600 spectral bands present, which were correlated with different elements by the German physicist Gustav Kirchhoff in 1859. Spectral observations of other stars revealed similar spectral bands, and hence similar compositions to the Sun.

SUBDISCIPLINES OF MODERN ASTRONOMY

One relatively newer goal of modern astronomy is to describe and characterize objects in the distant universe, with the Milky Way galaxy being recognized as a distinct and related group of stars only in the 20th century. This realization was followed by recognition of the expansion of the universe as described by Hubble's law, as well as distant objects such as quasars, pulsars, radio galaxies, black holes, and neutron stars.

The field of observational astronomy is based on data received from electromagnetic radiation from celestial objects and is divided into different subfields based on the wavelengths being studied. Radio astronomy deals with interpreting radiation received from celestial objects where the radiation has a wavelength greater than one millimeter, and is commonly used to study supernovae, interstellar gas, pulsars, and galactic nuclei. Radio astronomy uses wave theory to interpret these signals, since these long wavelengths are more easily assigned wavelengths and amplitudes than shorter wavelength forms of radiation. Most radio emissions from space received on Earth are a form of synchrotron radiation, produced when electrons oscillate in a magnetic field, although some is also associated with thermal emission from celestial objects, and interstellar gas is typically associated with 21-cm radio waves.

Infrared astronomy works with infrared wavelengths (longer than the wavelength of red light) and is used primarily to study areas such as planets and circumstellar disks that are too cold to radiate in the visible wavelengths of the electromagnetic spectrum. The longer infrared wavelengths are able to penetrate dust clouds, so infrared astronomy is also useful for observing processes such as star formation in molecular clouds and galactic cores blocked from observations in the visible wavelengths. Infrared astronomy observatories must be located in outer space or in high dry locations since the Earth's atmosphere is associated with significant infrared emissions.

Optical astronomy, the oldest form of observational astronomy, uses light recorded from the visible wavelengths. Most optical astronomy is now completed by using digital recording apparatus, speeding analysis. Ultraviolet astronomy (observations in the ultraviolet wavelengths) is used to study thermal radiation and the emission of spectral lines from hot blue stars, planetary nebula, supernova, and active galactic nuclei. Like infrared observatories, ultraviolet observation stations must be located in the upper atmosphere or in space, since ultraviolet rays are strongly absorbed by Earth's atmosphere.

The study and analysis of celestial objects at X-ray wavelengths is known as X-ray astronomy. X-ray emitters include some binary star systems, pulsars, supernova remnants, elliptical galaxies, galaxy clusters, and active galactic nuclei. X-rays are produced by celestial objects by thermal and synchrotron emission (generated by the oscillation of electrons around magnetic fields), but are absorbed by the Earth's atmosphere, so they must be observed from high-altitude balloons, rockets, or space. The study of the shortest wavelengths of the electromagnetic spectrum, known as gamma-ray astronomy, can so far be observed only by indirect observations of gamma ray bursts from objects including pulsars, neutron stars, and black holes near galactic nuclei.

See also ASTROPHYSICS; BLACK HOLES; CONSTELLATION; COSMOLOGY; GALAXIES; GALAXY CLUSTERS; ORIGIN AND EVOLUTION OF THE UNIVERSE; UNIVERSE.

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astrophysics Astrophysics is the branch of astronomy that examines the behavior, physical properties, and dynamic processes of celestial objects and phenomena. Astrophysics includes study of the luminosity, temperature, density, chemical composition, and other characteristics of celestial objects and aims at understanding the physical laws that explain these characteristics and behavior of celestial systems. Astrophysics is related to observational astronomy, as well as cosmology, the study of the theories related to the very large-scale structure and evolution of the universe. Astrophysicists study these systems using principles from different subfields in physics and astronomy, including thermodynamics, mechanics, electromagnetism, quantum mechanics, relativity, nuclear and particle physics, and atomic and molecular physics.

Much of astrophysics is founded on formulating theories based on observational astronomy using principles of quantum mechanics and relativity. Theoretical astrophysicists use analytical models and complex computational and numerical models of the behavior of celestial systems to understand better the origin and evolution of the universe and to test for unpredicted phenomena. In general theoretical models of celestial behavior are tested with the observations and constraints from astronomical studies, and the agreement (or lack thereof) between the model and the observed behavior is used to refine the models of celestial evolution.

Current topics of research in astrophysics include celestial and stellar dynamics and evolution, the large-scale structure of the universe, cosmology and the origin and evolution of the universe, models for galaxy formation, the physics of black holes, quasars, and phenomena such as gravity waves, and implications and tests of models of general relativity.

See also ASTRONOMY; BLACK HOLES; CONSTELLATION; COSMOLOGY; GALAXIES; GALAXY CLUSTERS; ORIGIN AND EVOLUTION OF THE UNIVERSE; UNIVERSE.

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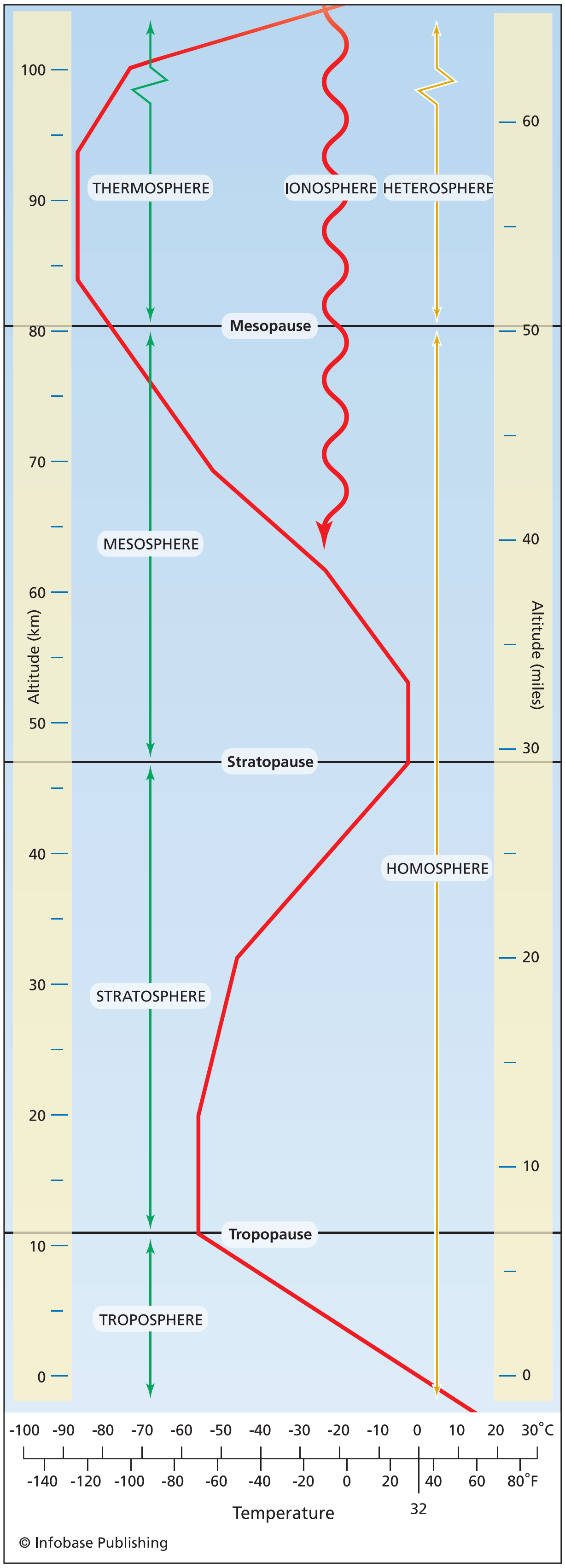
atmosphere Thin sphere around the Earth consisting of the mixture of gases we call air, held in place by gravity. The most abundant gas is nitrogen (78 percent), followed by oxygen (21 percent), argon (0.9 percent), carbon dioxide (0.036 percent), and minor amounts of helium, krypton, neon, and xenon. Atmospheric (or air) pressure is the force per unit area (similar to weight) that the air above a certain point exerts on any object below it. Atmospheric pressure causes most of the volume of the atmosphere to be compressed to 3.4 miles (5.5 km) above the Earth's surface, even though the entire atmosphere is hundreds of kilometers thick.

The atmosphere is always moving, because the equator receives more of the Sun's heat per unit area than the poles. The heated air expands and rises to where it spreads out, then it cools and sinks, and gradually returns to the equator. This pattern of global air circulation forms Hadley cells that mix air between the equator and midlatitudes. Similar circulation cells mix air in the middle to high latitudes, and between the poles and high latitudes. The effects of the Earth's rotation modify this simple picture of the atmosphere's circulation. The Coriolis effect causes any freely moving body in the Northern Hemisphere to veer to the right, and toward the left in the Southern Hemisphere. The combination of these effects forms the familiar trade winds, easterlies and westerlies, and doldrums.

The atmosphere is divided into several layers, based mainly on the vertical temperature gradients that vary significantly with height. Atmospheric pressure and air density both decrease more uniformly with height, and therefore are not a useful way to differentiate between different atmospheric layers.

The lower 36,000 feet (11,000 m) of the atmosphere, the troposphere, is where the temperature generally decreases gradually, at about 70°F per mile



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Structure of the atmosphere showing various layers and temperature profile with height

(6.4°C per km), with increasing height above the surface. This is because the Sun heats the surface, which in turn warms the lower part of the troposphere. Most of the familiar atmospheric and weather phenomena occur in the troposphere.

Above the troposphere is a boundary region known as the tropopause, marking the transition into the stratosphere. The stratosphere in turn continues to a height of about 31 miles (50 km). The base of the stratosphere contains a region known as an isothermal, where the temperature remains the same with increasing height. The tropopause is generally at higher elevations in summer than winter and is also the region where the jet streams are located. Jet streams are narrow, streamlike channels of air that flow at high velocities, often exceeding 115 miles per hour (100 knots). Above about 12.5 miles (20 km), the isothermal region gives way to the upper stratosphere, where temperatures increase with height, back to near surface temperatures at 31 miles (50 km). The heating of the stratosphere is due to ozone at this level absorbing ultraviolet radiation from the Sun.

The mesosphere lies above the stratosphere, extending between 31 and 53 miles (50–85 km). An isothermal region known as the stratopause separates the stratosphere and mesosphere. The air temperature in the mesosphere decreases dramatically above the stratopause, reaching a low of -130°F (-90°C) at the top of the mesosphere. The mesopause separates the mesosphere from the thermosphere, a hot layer where temperatures rise to more than 150°F (80°C). The relatively few oxygen molecules at this level absorb solar energy and heat quickly, and temperatures may change dramatically in this region in response to changing solar activity. The thermosphere continues to thin upward, extending to about 311 miles (500 km) above the surface. Above this level, atoms dissociate from molecules and are able to shoot outward and escape the gravitational pull of Earth. This far region of the atmosphere is sometimes referred to as the exosphere.

In addition to the temperature-based division of the atmosphere, it is possible to divide the atmosphere into different regions based on their chemical and other properties. Using such a scheme, the lower 46.5–62 miles (75–100 km) of the atmosphere may be referred to as the homosphere, which contains a well-mixed atmosphere with a fairly uniform ratio of gases from base to top. In the overlying heterosphere, the denser gases (oxygen and nitrogen) have settled to the base, whereas lighter gases (hydrogen and helium) have risen to greater heights, resulting in chemical differences with height.

The upper parts of the homosphere and the heterosphere contain a large number of electrically charged particles known as ions. Also called the ionosphere, this region strongly influences radio transmissions and the formation of the aurora borealis and aurora australis.

The production and destruction or removal of gases from the atmospheric system occur at approximately equal rates, although some gases are gradually increasing or decreasing in abundance, as described below. Soil bacteria and other biologic agents remove nitrogen from the atmosphere, whereas decay of organic material releases nitrogen back to the atmosphere. However, decaying organic material removes oxygen from the atmosphere by combining with other substances to produce oxides. Animals also remove oxygen from the atmosphere by breathing, whereas photosynthesis returns oxygen to the atmosphere.

Water vapor is an extremely important gas in the atmosphere, but it varies greatly in concentration (0–4 percent) from place to place and from time to time. Though water vapor is normally invisible, it becomes visible as clouds, fog, ice, and rain when the water molecules coalesce into larger groups. In the liquid or solid state, water constitutes the precipitation that falls to Earth and is the basis for the hydrologic cycle. Water vapor is also a major factor in heat transfer in the atmosphere. A kind of heat known as latent heat is released when water vapor turns into solid ice or liquid water. This heat, a major source of atmospheric energy, is a major contributor to the formation of thunderstorms, hurricanes, and other weather phenomena. Water vapor may also play a longer-term role in atmospheric regulation, as it is a greenhouse gas that absorbs a significant portion of the outgoing radiation from the Earth, causing the atmosphere to warm.

Carbon dioxide (CO_2), although small in concentration, is another very important gas in the Earth's atmosphere. Carbon dioxide is produced during decay of organic material, from volcanic outgassing, deforestation, burning of fossil fuels, and cow, termite, and other animal emissions. Plants take up carbon dioxide during photosynthesis, and many marine organisms use it for their shells, made of $CaCO_3$ (calcium carbonate). When these organisms (for instance, phytoplankton) die, their shells can sink to the bottom of the ocean and be buried, removing carbon dioxide from the atmospheric system. Like water vapor, carbon dioxide is a greenhouse gas that traps some of the outgoing solar radiation reflected from the earth, causing the atmosphere to warm up. Because carbon dioxide is released by the burning of fossil fuels, its concentration is increasing in the atmosphere as humans consume more fuel. The concentration of CO_2 in the atmosphere has increased by 15 percent since 1958, enough to cause considerable global warming. Estimates predict that the concentration of CO_2 will increase by another 35 percent by the end of the 21st century, further enhancing global warming.

Other gases also contribute to the greenhouse effect, notably methane (CH_4), nitrous oxide (NO_2) and chlorofluorocarbons (CFCs). Methane concentration is increasing in the atmosphere and is produced by the breakdown of organic material by bacteria in rice paddies and other environments, termites, and the stomachs of cows. Produced by microbes in the soil, NO_2 is also increasing in concentration by 1 percent every few years, even though it is destroyed by ultraviolet radiation in the atmosphere. Chlorofluorocarbons have received much attention since they are long-lived greenhouse gases increasing in atmospheric concentration as a result of human activity. Chlorofluorocarbons trap heat like other greenhouse gases, and also destroy ozone (O_3), a protective blanket that shields the Earth from harmful ultraviolet radiation. Chlorofluorocarbons were used widely as refrigerants and as propellants in spray cans. Their use has been largely curtailed, but since they have such a long residence time in the atmosphere, they are still destroying ozone and contributing to global warming, and will continue to do so for many years.

Ozone is found primarily in the upper atmosphere where free oxygen atoms combine with oxygen molecules (O_2) in the stratosphere. The loss of ozone has been dramatic in recent years, even leading to the formation of "ozone holes" with virtually no ozone present above the Arctic and Antarctic in the fall. There is currently debate about how much of the ozone loss is human-induced by chlorofluorocarbon production, and how much may be related to natural fluctuations in ozone concentration.

Many other gases and particulate matter play important roles in atmospheric phenomena. For instance, small amounts of sulfur dioxide (SO_2) produced by the burning of fossil fuels mixes with water to form sulfuric acid, the main harmful component of acid rain. Acid rain is killing the biota of many natural lake systems, particularly in the northeastern United States in areas underlain by granitic-type rocks, and it is causing a wide range of other environmental problems across the world. Other pollutants are major causes of respiratory problems and environmental degradation, and the major increase in particulate matter in the atmosphere in the past century has increased the hazards and health effects from these atmospheric particles.

AIR PRESSURE

The weight of the air above a given level is known as air pressure. This weight produces a force in all directions caused by constantly moving air molecules bumping into one another and other objects in the atmosphere. The air molecules in the atmosphere are constantly moving with each air molecule averaging a remarkable 10 billion collisions per second with other air molecules near the Earth's surface. The density of air molecules is highest near the surface, decreases rapidly upward in the lower 62 miles (100 km) of the atmosphere, then decreases slowly upward to above 310 miles (500 km). Gravity pulls air molecules toward the Earth, and they are therefore more abundant closer to the surface. Pressure, including air pressure, is measured as the force divided by the area over which it acts. The air pressure is greatest near the Earth's surface and decreases with height because there is a greater number of air molecules near the Earth's surface (the air pressure represents the sum of the total mass of air above a certain point). A one-square-inch column of air extending from sea level to the top of the atmosphere weighs about 14.7 pounds (6.67 kg). The typical air pressure at sea level is therefore 14.7 pounds per square inch (2.62 kg per square cm). It is commonly measured in units of millibars (mb) or hectopascals (hPa), and also in inches of mercury. Standard air pressure in these units equals 1,013.25 mb, 1,013.25 hPa, and 29.92 in of mercury. Air pressure is equal in all directions, unlike some pressures (such as a weight on one's head) that act in one direction. This explains why objects and people are not crushed or deformed by the pressure of the overlying atmosphere.

Air pressure also changes in response to temperature and density, as expressed by the following gas law:

$$\text{pressure} = \text{temperature} \times \text{density} \times \text{constant}$$

where the gas constant is equal to 2.87×10^6 erg/g K.

From this gas law it is apparent that at the same temperature, air at a higher pressure is denser than air at a lower pressure. Therefore high-pressure regions of the atmosphere are characterized by denser air, with more molecules of air than areas of low pressure. These pressure changes are caused by wind that moves air molecules into and out of a region. When more air molecules move into an area than move out, the area is called an area of net convergence. Conversely, in areas of low pressure, more air molecules are moving out than in, and the area is one of divergence. If the air density is constant and the temperature changes, the gas law states that at a given atmospheric level, as the temperature increases, the air pressure decreases. With these relationships, if either the temperature or the pressure is known, the other can be calculated.

If the air above a location is heated, it will expand and rise; if air is cooled, it will contract, become denser, and sink closer to the surface. Therefore the air pressure decreases rapidly with height in the cold column of air because the molecules are packed closely to the surface. In the warm column of air the air pressure will be higher at any height than in the cold column of air, because the air has expanded and more of the original air molecules are above the specific height than in the cold column. Therefore warm air masses at high height are generally associated with high-pressure systems, whereas cold air aloft is generally associated with low pressure. Heating and cooling of air above a location induces the air pressure to change in that location, causing lateral variation in air pressure across a region. Air will flow from high-pressure areas to low-pressure areas, forming winds.

The daily heating and cooling of air masses by the Sun can in some situations cause the opposite effect, if it is not overwhelmed by effects of the heating and cooling of the upper atmosphere. Over large continental areas, such as the southwestern United States, the daily heating and cooling cycle is associated with air pressure fall and rise, as expected from the gas law. As the temperature rises in these locations the pressure decreases, then increases again in the night when the temperature falls. Air must flow in and out of a given vertical column on a diurnal basis for these pressure changes to occur, as opposed to having the column rise and fall in response to the temperature changes.

ROLE OF THE ATMOSPHERE IN GLOBAL CLIMATE

Interactions among the atmosphere, hydrosphere, biosphere, and lithosphere control global climate. Global climate represents a balance between the amount of solar radiation received and the amount of this energy retained in a given area. The planet receives about 2.4 times as much heat in the equatorial regions compared to the polar regions. The atmosphere and oceans respond to this unequal heating by setting up currents and circulation systems that redistribute the heat more equally. These circulation patterns are in turn affected by the ever-changing pattern of the distribution of continents, oceans, and mountain ranges.

The amounts and types of gases in the atmosphere can modify the amount of incoming solar radiation, and hence global temperature. For instance, cloud cover can cause much of the incoming solar radiation to be reflected back to space before being trapped by the lower atmosphere. On the other hand, greenhouse gases allow incoming short wavelength solar radiation to enter the atmosphere, but trap this radiation when it tries to escape in its longer wavelength reflected form. This causes a buildup of heat in the atmosphere, and can lead to a global warming known as the greenhouse effect.

The amount of heat trapped in the atmosphere by greenhouse gases has varied greatly over Earth's history. One of the most important greenhouse gases is carbon dioxide (CO_2). Plants, which release O_2 to the atmosphere, now take up CO_2 by photosynthesis. In the early part of Earth's history (in the Precambrian before plants covered the land surface), photosynthesis did not remove CO_2 from the atmosphere, with the result that CO_2 levels were much higher than at present. Marine organisms remove atmospheric CO_2 from ocean surface water (which is in equilibrium with the atmosphere) and use the CO_2 along with calcium to form their shells and mineralized tissue. These organisms make $CaCO_3$ (calcite), which is the main component of limestone, a rock composed largely of the dead remains of marine organisms. Approximately 99 percent of the planet's CO_2 is presently removed from the atmosphere/ocean system because it is locked up in rock deposits of limestone on the continents and on the seafloor. If this amount of CO_2 were released back into the atmosphere, the global temperature would increase dramatically. In the early Precambrian, when this CO_2 was free in the atmosphere, global temperatures averaged about 550°F (290°C).

The atmosphere redistributes heat quickly by forming and redistributing clouds and uncondensed water vapor around the planet along atmospheric circulation cells. Oceans are able to hold and redistribute more heat because of their greater amount of water, but they redistribute this heat more slowly than the atmosphere. Surface currents form in response to wind patterns, but deep ocean currents that move more of the planet's heat follow courses more related to the bathymetry (topography of the seafloor) and the spinning of the Earth than they are related to surface winds.

The balance of incoming and outgoing heat from the Earth has determined the overall temperature of the planet through time. Examination of the geological record has enabled paleoclimatologists to reconstruct intervals when the Earth had glacial periods, hot dry episodes, hot wet, or cold dry cycles. In most cases the Earth has responded to these changes by expanding and contracting its climate belts. Warm periods see an expansion of the warm subtropical belts to high latitudes, and cold periods see an expansion of the cold climates of the poles to low latitudes.

HADLEY CELL

Hadley cells are the globe-encircling belts of air that rise along the equator and drop moisture as they rise in the Tropics. As the air moves away from the equator at high elevations, it cools, becomes drier, then descends at 15–30°N and S latitude, where it either returns to the equator or moves toward the poles.

The locations of the Hadley cells move north and south annually in response to the changing apparent seasonal movement of the Sun. High-pressure systems form where the air descends, characterized by stable clear skies and intense evaporation because the air is so dry. Another pair of major global circulation belts is formed as air cools at the poles and spreads toward the equator. Cold polar fronts form where the polar air mass meets the warmer air that has circulated around the Hadley cell from the Tropics. In the belts between the polar front and the Hadley cells, strong westerly winds develop. The position of the polar jet stream (formed in the upper troposphere), which is partly fixed in place in the Northern Hemisphere by the high Tibetan Plateau and the Rocky Mountains, controls the position of the polar front and extent of the west-moving wind. Dips and bends in the jet stream path are known as Rossby waves, and these partly determine the location of high- and low-pressure systems. These Rossby waves tend to be semistable in different seasons and have predictable patterns for summer and winter. If the pattern of Rossby waves in the jet stream changes significantly for a season or longer, storm systems may track to different locations than normal, causing local droughts or floods. Changes in this global circulation can also change the locations of regional downwelling, cold dry air. This can cause long-term drought and desertification. Such changes can persist for periods of several weeks, months, or years, and may explain several of the severe droughts that have affected Asia, Africa, North America, and elsewhere.

JET STREAMS

Jet streams are high-level, narrow, fast-moving currents of air typically thousands of kilometers long, hundreds of kilometers wide, and a couple of miles (several kilometers) deep. Jet streams typically form near the tropopause, six to nine miles (10–15 km) above the surface, and can reach speeds of 115–230 miles per hour (100–200 knots). Rapidly moving cirrus clouds often reveal the westerly jet streams moving air from west to east. Several jet streams are common—the subtropical jet stream forms about eight miles (13 km) above the surface, at the poleward limit of the tropical Hadley cell, where a tropospheric gap develops between the circulating Hadley cells. The polar jet stream forms at about a six-mile (10-km) height, at the tropospheric gap between the cold polar cell and the midlatitude Ferrel cell. The polar jet stream is often associated with polar front depressions. The jet streams, especially the subtropical jet, are fairly stable and drive many of the planet's weather systems. The polar jet stream tends to meander and develop loops more than the subtropical jet. A third common jet stream often develops as an easterly flow, especially over the Indian subcontinent during the summer monsoon.

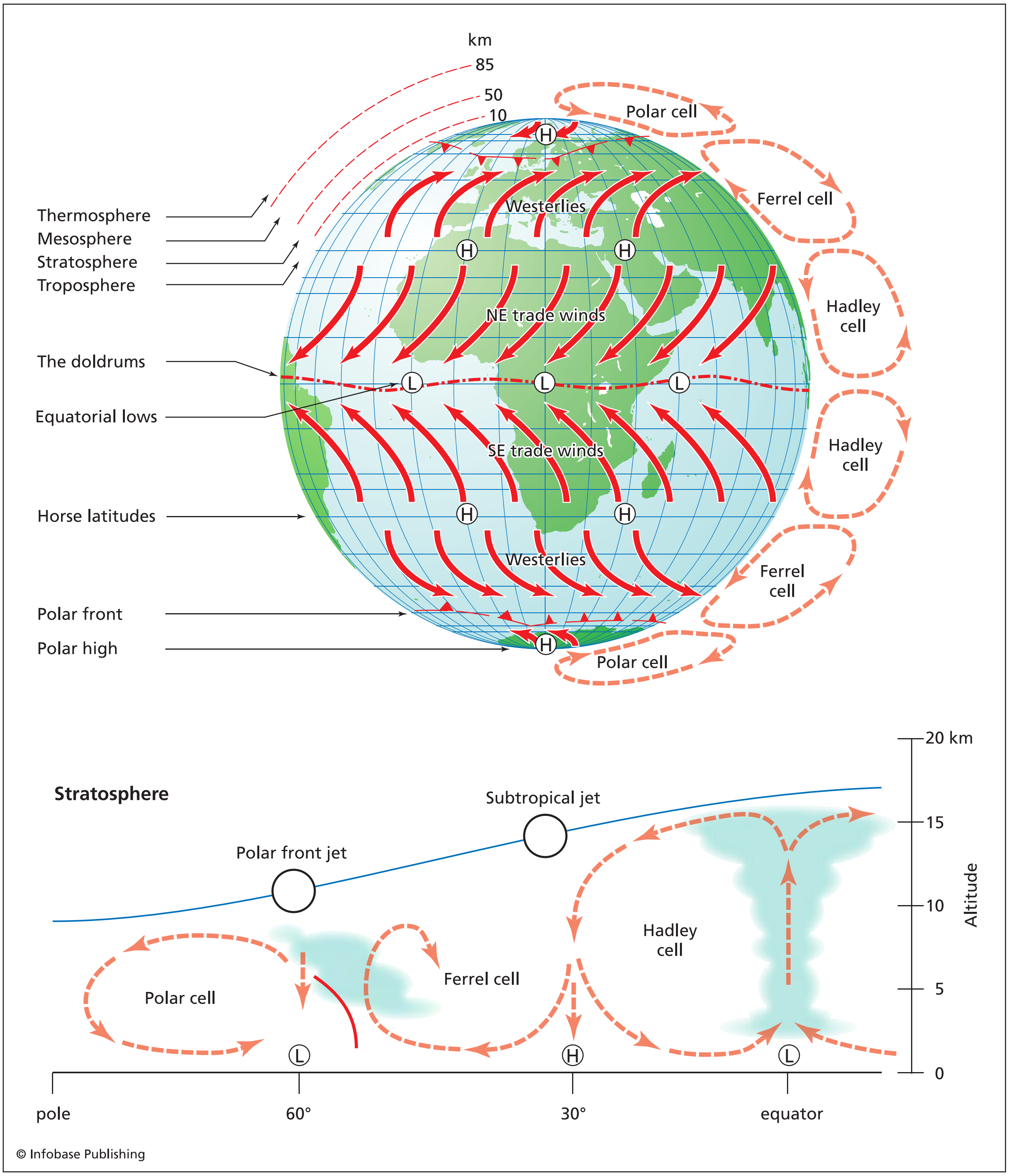
ATMOSPHERIC EVOLUTION

Considerable uncertainty exists about the origin and composition of the Earth's earliest atmosphere. Many models assume that methane and ammonia dominated the planet's early atmosphere, instead of nitrogen and carbon dioxide, as it is presently. The gases that formed the early atmosphere could have come from outgassing by volcanoes, from extraterrestrial sources (principally cometary impacts), or, most likely, both. Alternatively, comets may have brought organic molecules to Earth. A very large late impact is thought to have melted outer parts of the Earth, formed the Moon, and blown away the earliest atmosphere. The present atmosphere must therefore represent a later, secondary atmosphere formed after this late impact.

The earliest atmosphere and oceans of the Earth probably formed from early degassing of the interior by volcanism within the first 50 million years of Earth history. It is likely that our present atmosphere is secondary, in that the first, or primary, atmosphere would have been vaporized by the late great impact that formed the Moon, if it survived being blown away by an intense solar wind when the Sun was in a T-Tauri stage of evolution. The primary atmosphere would have been composed of gases left over from accretion, including primarily hydrogen, helium, methane, and ammonia, along with nitrogen, argon, and neon. Since the atmosphere has much less than the expected amount of these elements, however, and is quite depleted in these volatile elements relative to the Sun, it is thought the primary atmosphere has been lost to space.

Gases are presently escaping from the Earth during volcanic eruptions, and also being released by weathering of surface rocks. The secondary atmosphere was most likely produced from degassing of the mantle by volcanic eruptions, and perhaps also by cometary impact. Gases released from volcanic eruptions include N, S, CO_2, and H_2O, closely matching the suite of volatiles that the present atmosphere and oceans comprise. But there was little or no free oxygen in the early atmosphere, as oxygen was not produced until later, by photosynthetic life.

The early atmosphere was dense, with H_2O, CO_2, S, N, HCl. The mixture of gases in the early atmosphere would have made greenhouse conditions similar to that presently existing on Venus. But, since the early Sun during the Hadean Era was approximately 25 percent less luminous than today, the atmospheric greenhouse kept temperatures close to their present range, where water is stable



Major atmosphere circulation patterns on the Earth, in map view (top), and in cross section (bottom)

and life can form and exist. As the Earth cooled, water vapor condensed to make rain that chemically weathered igneous crust, making sediments. Gases dissolved in the rain made acids, including carbonic acid (H_2CO_3), nitric acid (HNO_3), sulfuric acid (H_2SO_4), and hydrochloric acid (HCl). These acids were neutralized by minerals (which are bases) that became sediments, and chemical cycling began. These waters plus dissolved components became the early hydrosphere, and chemical reactions gradually began changing the composition of the atmosphere, getting close to the dawn of life.

During the early Archean, the Sun was only about 70 percent as luminous as it is presently, so the Earth must have experienced a greenhouse warming effect to keep temperatures above the freezing point of water, but below the boiling point. Increased levels of carbon dioxide and ammonia in the early atmosphere could have acted as greenhouse gases, accounting for the remarkable maintenance of global temperatures within the stability field of liquid water, allowing the development of life. Much of the carbon dioxide that was in the early atmosphere is now locked up in deposits of sedimentary limestone, and in the planet's biomass. The carbon dioxide that shielded the early Earth and kept temperatures in the range suitable for life to evolve now forms the bodies and remains of those very life-forms.

See also AURORA, AURORA BOREALIS, AURORA AUSTRALIS; CLIMATE; CLIMATE CHANGE; GREENHOUSE EFFECT; WEATHERING.

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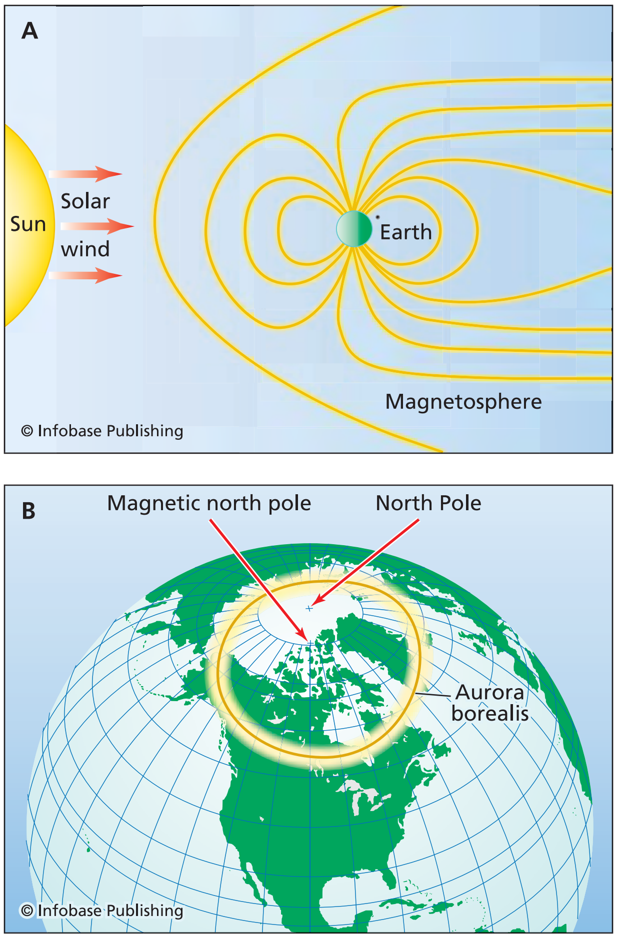
aurora, aurora borealis, aurora australis

Auroras Borealis and Aurora Australis are glows in the sky sometimes visible in the Northern and Southern Hemispheres, respectively. They are informally known as the northern lights and the southern lights. The glows are strongest near the poles, and originate in the Van Allen radiation belts, regions where high-energy charged particles of the solar wind that travel outward from the Sun are captured by the Earth's magnetic field. The outer Van Allen radiation belt consists mainly of protons, whereas the inner Van Allen belt consists mainly of electrons. At times electrons spiral down toward Earth near the poles along magnetic field lines and collide with ions in the thermosphere, emitting light in the process. Light in the aurora is emitted between a base level of about 50–65 miles (80–105 km), and an upper level of about 125 miles (200 km) above the Earth's surface.

The solar wind originates when violent collisions between gases in the Sun emit electrons and protons that escape the gravitational pull of the Sun and travel through space at about 250 miles per second (more than 1 million km/hr) as a plasma known as the solar wind. When these charged particles move close to Earth, they interact with the magnetic field, changing its shape in the process. The natural undisturbed state of the Earth's magnetic field is broadly similar to a bar magnet, with magnetic flux lines (of equal magnetic intensity and direction) coming out of the south polar region, and returning into the north magnetic pole. The solar wind deforms or distorts this ideal state into an elongate teardrop-shaped configuration known as the magnetosphere. The magnetosphere has a rounded compressed side facing the Sun, and a long tail (magnetotail) on the opposite side that stretches past the orbit of the moon. The magnetosphere shields the Earth from many of the charged particles from the Sun by deflecting them around the edge of the magnetosphere, causing them to flow harmlessly into the outer solar system.



(A) Drawing of magnetosphere, showing asymmetric shape created by distortion of the Earth's magnetic field by the solar wind (B) Earth, showing typical auroral ring with the greatest intensity of auroral activity about 20–30° from the magnetic pole, where magnetic field lines are most intense

Active aurora borealis arc in Alaska *(Roman Krochuk, Shutterstock, Inc.)*

The Sun periodically experiences periods of high activity when many solar flares and sunspots form. During these periods the solar wind is emitted with increased intensity, and the plasma is emitted with greater velocity, in greater density, and with more energy than in its normal state. During these periods of high solar activity the extra energy of the solar wind distorts the magnetosphere and causes more electrons to enter the Van Allen belts, causing increased auroral activity.

When the electrons from the magnetosphere are injected into the upper atmosphere, they collide with atoms and molecules of gases there. The process involves the transfer of energy from the high-energy particles of the magnetosphere to the gas molecules from the atmosphere, which become excited and temporarily jump to a higher energy level. When the gas molecules return to their normal, regular energy level, they release radiation energy in the process. Some of this radiation is in the visible spectrum, forming the aurora borealis in the Northern Hemisphere and the aurora australis in the Southern Hemisphere.

Auroras typically form waving sheets, streaks, and glows of different colors in polar latitudes. The colors originate because different gases in the atmosphere emit different characteristic colors when excited by charged particles from the magnetosphere, and the flickering and draperies are caused by variations in the magnetic field and incoming charged particles. The auroras often form rings around the magnetic poles, being most intense where the magnetic field lines enter and exit the Earth at 60–70° latitude.

See also MAGNETIC FIELD, MAGNETOSPHERE; SUN.

Australian geology The geologic history of Australia spans almost all of the history of the Earth, hosting the oldest known terrestrial mineral grains dated to be 4.4 billion years old. The region contains active deposition of lake sediments in the desert interior and some of the world's most diverse carbonate reefs located offshore its northeast coastline. The geology of Australia can be divided into provinces of several ages, including the Archean Pilbara, Yilgarn, Kimberly, and Gawler cratons, which are encased in Proterozoic orogenic belts including the Musgrave orogen and Arunta Inlier. Paleozoic orogens include the Lachlan and Tasman orogens in the east, whereas the northern and northeastern edges of the Australia plate are involved in active convergent tectonic activity. Mesozoic to recent sedimentary basins in Australia include the Perth and Bowen basins; Sydney, Gunnedah, and Ipswich basins; and the large active desert drainage system of Lake Eyre in the Australian midcontinent.

ARCHEAN CRATONS

Archean rocks form the core of the Australian continent and include the cratonic nuclei of the Yilgarn, Plibara, Gawler, and Kimberly cratons. Archean rocks may also underlie portions of some of the Proterozoic basins and orogens, but less is known about the rocks at great depths in Australia.

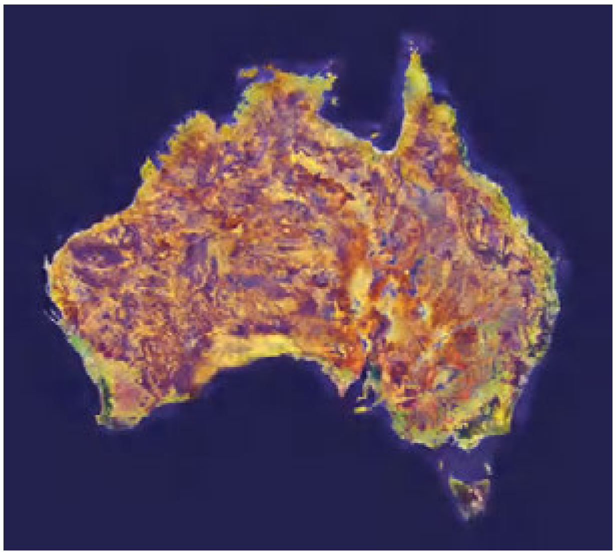
The Pilbara craton, located in northwestern Australia, contains mainly low- to medium-grade Archean rocks with the metavolcanic and metasedimentary rocks confined to relatively narrow belts between broad domal granitoid-gneiss domes typically 50–60 miles (~100 km) in width. Early ideas that the greenstones and metasedimentary rocks were simply deposited on top of older granitoids then later deformed by folding as their density caused them to sink into rheologically soft granitoids have proven to be myths. Detailed structural analysis has shown that the greenstones were emplaced structurally upon the gneissic and granitoid rocks, then deformed several times before the late open folding caused by the doming of the granitoids.

The granitoid rocks of the domal structures are of four basic types: older migmatitic, gneissic and foliated granodiorites, tonalites, and trondhjemites, in turn intruded by coarse-grained porphyritic granodiorite and then unfoliated post-tectonic granites. The older gneissic rocks range in age from 3.5 to 3.3 billion years, whereas the younger intrusives are between 3.05 and 2.85 billion years old. The domes in the Pilbara are not formed by intrusion-related processes, but rather reflect complex, large-scale folding events. Much of the doming occurred at 3.0–2.95 billion years ago in a cratonwide event.

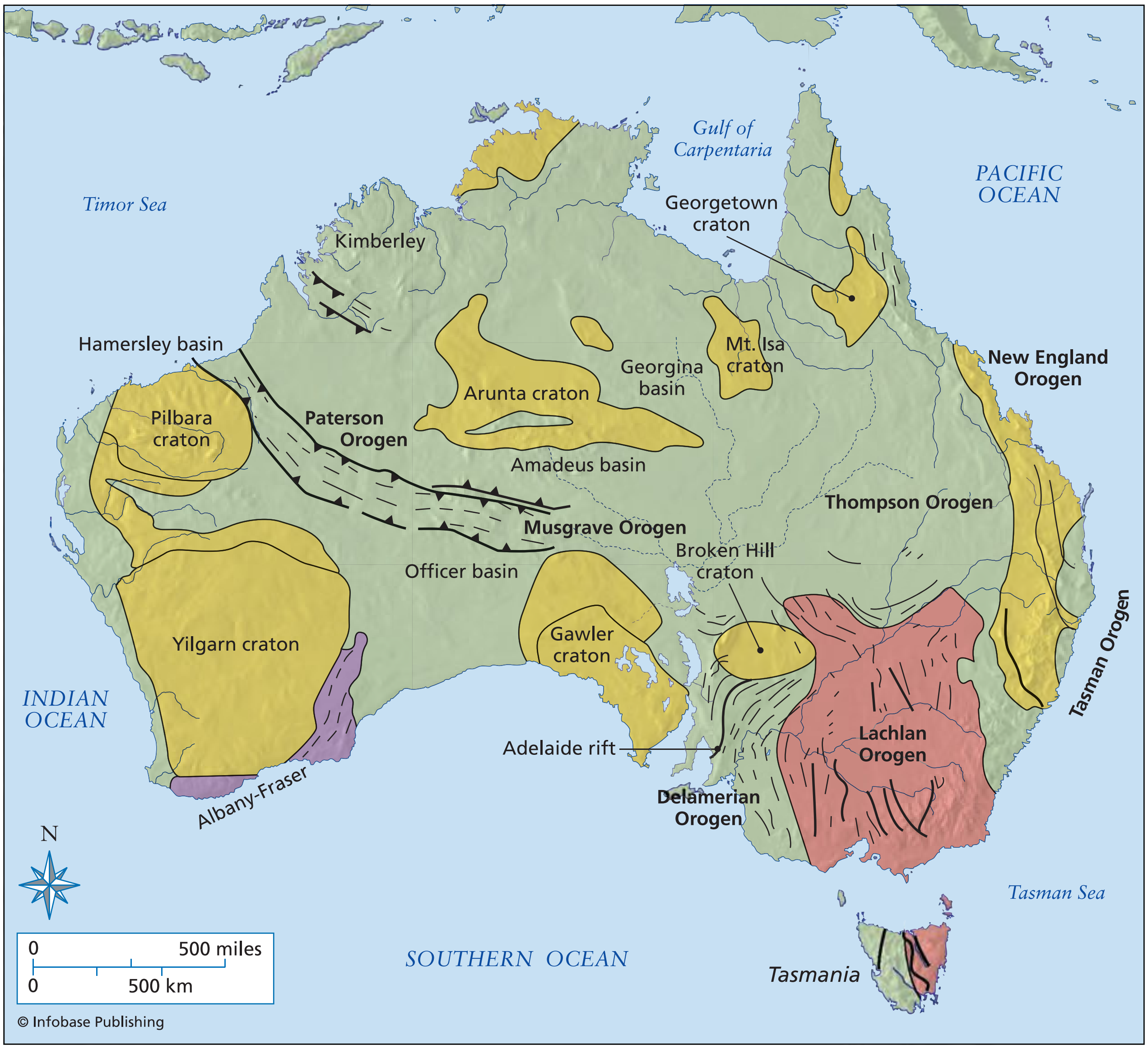
The metavolcanic and sedimentary rocks between the domal granitoids, known as the Pilbara Supergroup, comprise three groups: the Warrawoona, George Creek, and Whim Creek sequences. Nowhere can it be shown that these rocks were deposited on the older gneissic rocks, though some groups argue that the entire sequence was deposited on continental basement, and others argue the supergroup is an allochthonous (exotic and far traveled) assemblage emplaced on the gneisses by thrusting and tectonic processes. Some of the rock sequences within the Pilbara Supergroup are calc-alkaline volcanic assemblages that resemble younger island arc sequences, and others are tholeiitic mafic volcanic and plutonic sequences that resemble younger ocean floor assemblages. These rocks are significantly disrupted and repeated along many thin shear zones and intercalated with sedimentary rocks in a manner like many younger accretionary prisms found at convergent margins, so some interpretations of the Pilbara suggest that it may represent an ancient accretionary orogen, formed at 3.5 billion years ago and disrupted by collisional tectonic events between 3.5 and 2.8 billion years ago.

The southern margin of the Pilbara craton and northern margin of the Yilgarn is covered by thick sedimentary deposits of the Hamersley and Nabberu basins, including spectacular banded-iron formations (BIF). The Mount Bruce Supergroup of the Hamersley basin includes thick deposits of clastic and chemical sediments divided into the lower Fortescue Group containing mafic volcanics, the 1.3-mile (2.5-km) thick Middle Hamersley Group consisting of banded-iron formation, shale, dolostone, and fewer diabasic intrusions and felsic volcanics. The uppermost rocks in the basin include shales, sandstones, and glacial deposits of the Turee Creek Group. The Hamersley Group is marked by thin layers of BIF that are remarkably continuous over thousands of square miles (km^2) and contain roughly 30 percent iron, making these rocks a significant economic resource. The Hamersley basin is deformed into a regional synclinorium structure, and only weakly metamorphosed, with dips of strata typically fewer than 10 degrees. The ages of these rocks include an estimate of 2.49 billion years for the Hamersley Group, and all groups in the basin are cut by intrusives dated between 2.4 and 2.3 billion years old.

The Yilgarn craton occupies the southwestern part of the Australian continent, covering an area



Satellite image mosaic of Australia, consisting of more than 1,000 merged images *(Earth Satellite Corporation/Photo Researchers, Inc.)*



Geological map of Australia, showing the main tectonic elements including the Archean cratons and younger orogens

600 miles (1,000 km) long by 420 miles (700 km) across. The craton is subdivided into four major provinces including a dominantly gneissic terrane, the Western Gneiss Terrane in the southwest, and then low-to-medium–grade granite-greenstone terranes of the Murchison Province in the northwest, the Southern Cross Province in the center of the craton, and the Eastern Goldfields in the east. All of the belts in the Yilgarn craton were affected by a regional metamorphic and plutonic intrusion event at 2.7–2.6 billion years ago.

The Western Gneiss Terrane consists mainly of quartzofeldspathic gneiss derived from sedimentary protoliths, then intruded by migmatitic to porphyritic granitoids. The Narryer Gneiss Complex in the northern part of the terrane includes layers of metamorphosed conglomerates, sandstones, pelites, and carbonate rocks and is interpreted as a strongly metamorphosed shallow water sedimentary sequence. Clastic zircons from the Narrier Complex have yielded many ancient zircons with ages from 3.6 to 3.5 billion years ago, and one sample dated by Australian geologist Simon Wilde has yielded an age of 4.4 billion years, a mere 100 million years after the formation of the Earth. Geochemical analysis of this zircon grain by Simon Wilde and his colleagues has shown that the zircon was derived from a rock that interacted with the early hydrosphere of the Earth, showing that oceans existed on Earth by 4.4 billion years ago.

The Murchison, Southern Cross, and Eastern Goldfields Provinces are all dominated by different types of granitoid and gneissic rocks, with about 30 percent of the outcrop area consisting of greenstone belts and metasedimentary terrains. Most of these strike roughly north-northwest and have broad synclinal structures disrupted by numerous faults, reflecting their complex history. These rocks include tholeiitic basalts and ultramafic rocks near the base of most successions, with felsic volcanic rocks and clastic sedimentary rocks at the tops of the successions. Ages on the volcanics range from 3.05 to 2.69 billion years. Some models for the volcanic groups suggest that the repetitive sequences from mafic to felsic volcanics are depositional, whereas others have suggested that thrust faults repeat the stratigraphic sequence.

Late-stage major ductile transcurrent shear zones cut the Yilgarn craton and form many of the boundaries between different belts and terranes. The 186-mile (300-km) long Koolyanobbing shear zone in the Southern Cross Province is a four- to nine-mile (6- to 15-km) wide zone with a gradation from foliated granitoid, through protomylonite, mylonite, to ultramylonite, from the edge to the center of the shear zone. Shallowly plunging lineations and a variety of kinematic indicators show that the shear zone is a major sinistral fault, but regional relationships suggest that it does not represent a major crustal boundary or suture. Fault fabrics both overprint and appear coeval with late stages in the development of the regional metamorphic pattern, suggesting that the shear zone was active around 2.7 to 2.65 Ga.

The granitoid intrusives in the Yilgarn craton account for about 70 percent of the outcrop area. These include 2.9–2.6 billion-year-old tonalitic to granodioritic phases, and 2.7–2.6 billion-year-old granodiorite to granite. The older granitoids have geochemical affinities to convergent margin arc magmas, whereas the younger granitoids may be related to post-collisional melting such as characterizes many younger convergent and collisional mountain belts in Phanerozoic orogens.

The Gawler craton is a relatively small block located in areas surrounding the Eyre Peninsula in south-central Australia, and is younger than the Pilbara and Yilgarn. It contains rocks that formed in convergent margins between 2.5 and 1.5 billion years ago, then became relatively stable after an orogenic event between 1.9 and 1.84 billion years ago, probably reflecting the incorporation of the block into the Rodinian supercontinent.

Hamersley Gorge on the margin of the Pilbara craton, Australia, showing red banded-iron formation *(imagebroker/Alamy)*

The Kimberly block of northern Australia is thought to be an Archean craton, but it is covered by thick deposits of the Kimberly basin. This block is bounded on the southeast by the Halls Creek belt and on the southwest by the King Leopold belt, both of which are Proterozoic orogenic belts that experienced strong deformation in the Barramundi orogeny at 1.85 billion years ago. After this major deformation event the Kimberly block was covered by up to three miles (five km) of uniformly bedded quartz sandstones, shales, limestones, and flood basalts.

PROTEROZOIC GNEISS BELTS AND BASINS

The Archean cratons of Australia are welded together by several Proterozoic orogenic belts, the most important of which include the Musgrave orogen and its continuation to the west as the Paterson orogen that together link north and south Australia. The Capricorn orogen is located between the Pilbara and Yilgarn cratons; convergent tectonism across this belt joined those cratons and their flanking sedimentary basin sequences in the Paleoproterozoic at around 2.2 billion years ago, with remnants preserved in the Bangemall basin, Gascoyne Complex, and the Glengarry, Yerrida and Padbury basins. Other Paleoproterozoic orogenic segments in central Australia are deeply buried by younger Proterozoic-Palaeozoic rocks of the Officer and Amadeus basins.

In eastern Australia rocks in the Mount Isa Complex were complexly deformed into fold-thrust belt structures in the Paleoproterozoic, while rocks farther south in the Broken Hill Inlier were experiencing high-grade metamorphism and polyphase deformation.

PHANEROZOIC OROGENS AND BASINS

The main area of Phanerozoic deformation and activity in Australia is along the east coast, in the Lachlan fold belt and Tasman orogen. The Lachlan fold belt contains Cambrian ophiolitic sequences that were thrust on top of the Australian continent in the Ordovician in the Lachlan Orogeny. This orogeny was associated with many classical Alpine-type events including the formation of flysch and molasse belts, strongly deformed zones with serpentinitic and ophiolitic mélange, and affected a large part of the New South Wales region of Australia. Tectonic activity continued in this belt through the Silurian with the formation of volcanic arcs in the New England orogen and the intrusion of belts of granitic batholiths. The high topography formed in the east during the Early Paleozoic was significantly eroded in the Devonian, with thick clastic sequences reaching into the continental interior.

In the Carboniferous eastern Australia collided with parts of South America and New Zealand as part of the amalgamation of the Gondwanan supercontinent; this collision formed high, Tibetan-style mountain ranges on the east coast. These ranges have since been nearly completely eroded, and just their deeper-level roots remain as testimony to this event.

The Permian-Triassic saw the establishment of major subduction zones along the east coast in the Hunter-Bowen Orogeny, which was initiated as an arc colliding with Australia and then conversion of this margin to a convergent tectonic setting, with related deformation continuing until the Middle Triassic at 230–225 million years ago. A major glaciation event in the Permian caused accelerated erosion of these mountain ranges, particularly in central and western Australia. Glacial tillite deposits from this event cover large parts of central Australia.

The environment of the Jurassic changed such that most of western Australia experienced tropical weathering in a savanna to jungle setting, and several offshore oil basins formed including the Gippsland, Bass, and Otway basins in Victoria. Coal-bearing strata were laid down across northern Australia, while passive margin sedimentation continued in the Perth basin in the west.

Antarctica rifted from Australia in the Jurassic. Rift-sedimentation and subsidence continued in the Cretaceous and developed into seafloor spreading and the separation of Tasmania from the Australian mainland. These rifted to passive margins, then developed extensive coral reefs in the northeast, and rare intraplate volcanic centers formed through the Tertiary.

GREAT BARRIER REEF

As the largest coral reef in the world, the Great Barrier Reef forms a 1,250-mile (2,010-km) long breakwater in the Coral Sea along the northeast coast of Queensland, Australia. The reef has been designated a World Heritage area, the world's largest such site. The reef comprises several individual reef complexes including 2,800 individual reefs stretching from the Swain reefs in the south to the Warrier reefs along the southern coast of Papua New Guinea. Many reef types are recognized including fringing reefs, flat platform reefs, and elongate ribbon reefs. The reef complexes are separated from the mainland of Queensland by a shallow lagoon ranging from 10 to 100 miles (16–160 km) wide.

There are more than 400 types of coral known on the Great Barrier Reef, as well as 1,500 species of fish, 400 species of sponges, and 4,000 types of mollusk, making it one of the world's richest sites in terms of faunal diversity. Additionally, the reefs are home to animals including numerous sea anemones, worms, crustaceans, echinoderms, and an endangered mammal known as the dugong. Sea turtles feed on abundant algae and sea grass, and the reef is frequented by humpback whales that migrate from Antarctic waters to have babies in warm waters. Hundreds of bird species have breeding colonies in the islands and cays among the reefs, and these birds include beautiful herons, pelicans, osprey, eagles, and shearwaters.

The reefs also hide dozens of shipwrecks and have numerous archaeological sites of significance to the Aboriginal and Torres Strait Islander peoples.

LAKE EYRE

The center of Australia is covered by a shallow, frequently dry salt lake that occupies the lowest point on the continent, at 39 feet (12 m) below sea level. The lake occupies 3,430 square miles (8,884 km^2), but the drainage basin is one of the world's largest internally draining river systems covering 1.2 million square miles (1.93 million km^2), with no outlet to the sea. All water that enters the Lake Eyre basin flows into the lake and eventually evaporates, leaving salts behind. Lake Eyre is located in the driest part of Australia, where the evaporation potential is 8.175 feet (2.5 m), but the annual precipitation is only half an inch (1.25 centimeters). However, flows in the river system are highly variable and unpredictable, since rare rainfall events may cause flash flooding. All rivers in the system are ephemeral, typically with no water in the system. Aridity increases downstream toward the lake, and the basin is characterized by huge braided stream networks, floodplains, and waterholes. The stream systems leading into Lake Eyre are one of the largest unregulated river systems in the world.

See also ARCHEAN; BASIN, SEDIMENTARY BASIN; CONVERGENT PLATE MARGIN PROCESSES; CRATON; DESERTS; DIVERGENT PLATE MARGIN PROCESSES; GONDWANA, GONDWANALAND; GREENSTONE BELTS; HISTORICAL GEOLOGY; OPHIOLITES; PASSIVE MARGIN; PLATE TECTONICS.

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B

basin, sedimentary basin A depression in the surface of the Earth or other celestial body is known as a basin. When this depression becomes filled with sediments, it is known as a sedimentary basin. There are many types of basins, including depressed areas with no outlet or with no outlet for deep levels (such as lakes, oceans, seas, and tidal basins), and areas of extreme land subsidence (such as volcanic calderas or sinkholes). In contrast, drainage basins include the total land area that contributes water to a stream. Drainage (river or stream) basins are geographic areas defined by surface slopes and stream networks where all the surface water that falls in the drainage basin flows into that stream system or its tributaries. Groundwater basins are areas where all the groundwater is contained in one system, or flows toward the same surface water basin outlet. Impact basins are circular depressions excavated instantaneously during the impact of a comet or asteroid with the Earth or other planetary surface.

Areas of prolonged subsidence and sediment accumulation are known as sedimentary basins, even though they may not presently be topographically depressed. Several types of sedimentary basins exist and are classified by their shape and relationships to bordering mountain belts or uplifted areas. Foreland basins are elongate areas on the stable continent sides of orogenic belts, characterized by a gradually deepening, generally wedge-shaped basin, filled by clastic and lesser amounts of carbonate and marine sedimentary deposits. The sediments are coarser-grained and of more proximal varieties toward the mountain front, from where they were derived. Foreland basins may be several hundred feet to about 12 miles (100 meters to 20 km) deep and filled entirely by sedimentary rocks, and are therefore good sites for hydrocarbon exploration. Many foreland basins have been overridden by the orogenic belts from where they were derived, producing a foreland fold-thrust belt, and parts of the basin incorporated into the orogen. Many foreland basins show a vertical profile from a basal continental shelf type of assemblage, made up dominantly of limestone, upward to a greywacke/shale flysch sequence, into an upper conglomerate/sandstone sequence known as molasse.

Rift basins are elongate depressions in the Earth's surface in which the entire thickness of the lithosphere has ruptured in extension. They are typically bounded by normal faults along their long sides, and display rapid lateral variation in sedimentary facies and thicknesses. Rock types deposited in the rift basins include marginal conglomerate, fanglomerate, and alluvial fans, grading basinward into sandstone, shale, and lake evaporite deposits. Volcanic rocks may be intercalated with the sedimentary deposits of rifts, and in many cases include a bimodal suite of basalts and rhyolites, some with alkaline chemical characteristics.

Several other less common types of sedimentary basins form in different tectonic settings. For instance, pull-apart rift basins and small foreland basins may form along bends in strike-slip fault systems, and many varieties of rift and foreland basins form in different convergent margin and divergent margin tectonic settings.

FORELAND BASINS

Foreland basins are wedge-shaped sedimentary basins that form on the continentward side of fold-thrust belts, filling the topographic depression created by the weight of the mountain belt. Most foreland basins have asymmetric, broadly wedge-shaped profiles with the deeper side located toward the mountain range, and a flexural bulge developed about 90 miles (150 km) from the foothills of the mountains where the deformation front is located. The Indo-Gangetic plain on the south side of the Himalaya Mountains is an example of an active foreland basin, whereas some ancient examples include the Cretaceous Canadian Rockies Alberta foreland basin, the Cenozoic flysch basins of the Alps, and the Ordovician and Devonian clastic wedges in the Appalachian foreland basins. Foreland basins are characterized by asymmetric subsidence, with greater amounts near the thrust front. Typical amounts of sudsidence fall in the range of about 0.6 miles (1 km) every 2 to 5 million years.

Deformation such as folding, thrust faulting, and repetition of stratigraphic units may affect foreland basins near the transition to the mountain front. These types of foreland basins appear to have formed largely by the flexure of the lithosphere by the weight of the mountain range, with the space created by the flexure filled in by sediments eroded from the uplifted mountains. Sedimentary facies typically grade from fluvial/alluvial systems near the mountains to shallow marine clastic environments farther away from the mountains, with typical deposition of flysch sequences by turbidity currents. These deposits may be succeeded laterally by distal black shales, then shallow water carbonates over a cross-strike distance of several hundred miles (kilometers). There is also often a progressive zonation of structural features across the foreland basin, with contractional deformation (folds and faults) affecting the region near the mountain front, and normal faulting affecting the area on the flexural bulge a few tens to hundreds of kilometers from the deformation front. Sedimentary facies and structural zones all may migrate toward the continent in collisional foreland basins.

A second variety of foreland basin is found on the continentward side of noncollisional mountain belts such as the Andes, and these are sometimes referred to as retroarc foreland basins. They differ from the collisional foreland basins described above in that the mountain ranges are not advancing on the foreland, and the basin subsidence is a response to the weight of the mountains, added primarily by magmatism.

Another variety of foreland basins, known as extensional foreland basins, include features such as impactogens and aulacogens, which are extensional basins that form at wide angles to the mountain front. Impactogens form during the convergence, whereas aulacogens are reactivated rifts that formed during earlier ocean opening. Many of these basins have earlier structural histories, including formation as a rift at a high angle to an ocean margin. These rifts are naturally oriented at wide angles to the mountain ranges when the oceans close, and become sites of enhanced subsidence, sedimentation, and locally additional extension. The Rhine graben in front of the Alpine collision of Europe is a well-known example of an aulacogen.

RIFTS

Active rift systems may exhibit very steep escarpments that drop from the rift shoulders to the base of the rift valley floor, typically forming an elongate depression that may extend for hundreds or even thousands of miles. The world's best known example of a continental rift is the East African rift, extending from the Ethiopian Afar to Mozambique. Other spectacular examples include Lake Baikal in Siberia, the Rio Grande in the desert southwest of Arizona and New Mexico, and the Alaotra rift in Madagascar. Most of these rifts have coarse-grained sediments deposited along their margins, and fine-grained and even lake sediments in their centers. Volcanic centers are sporadically developed.

Many rifts in continents are associated with incipient breaking apart of the continent to form an oceanic basin. These types of rift system typically form three arms that develop over domed areas above upwelling mantle material, such as is observed in east Africa. Two of the three arms may link with other three-pronged rift systems developed over adjacent domes, forming a linked elongate rift system that then spreads to form an ocean basin. This type of development leaves behind some failed rift arms that will come to reside on the margins of young oceans when the successful rift arms begin to spread. These failed rift arms then become sites of increased sedimentation and subsidence, and also tend to be low-lying areas, and form the tectonic setting where many of the world's major rivers flow (for example, the Nile, Amazon, and Mississippi). Other rifts form at high angles to collisional mountain belts, and still others form in regions of widespread continental extension such as the basin and range province of the southwestern United States.

PULL-APART BASIN

Pull-apart basins are elongate depressions that develop along extensional steps on strike-slip faults. Pull-apart basins are features that develop in transtensional regions, in which the principal stresses are compressional, but some areas within the region are under extension due to the obliquity of the major stress direction with respect to the plane of failure. This results in extension of the crust along releasing bends, leading to a break in the crust and the formation of basins. Some pull-apart basins show several progressive stages in their formation. Others initiate along a fracture, and progress into lazy Z or S shapes, and finally progress into a basin that ranges in length-to-width ratio from 2:1 to 10:1. These types of basins are characterized by steep sides on major fault boundaries with normal faults developing on their shorter sides. Continuous movement along the major faults tends to offset deposits from their source inlet to the basin. These basins are characterized by rapid deposition and rapid facies changes along or across the width of the basin and gradual facies change along the longest axis of the basin. Pull-apart basin deposits are typically made mostly of coarse fanglomerate, conglomerate, sandstone, shales, and shallow water limestones and evaporites. Bimodal volcanics and volcanic sediments are also found interbedded within the basin deposits. These bimodal volcanics are typical of those found in rift settings, but here they are in a transtensional regime. Transcurrent faults can penetrate down deep into the crust, reaching the upper mantle and providing a conduit for magma.

See also CONVERGENT PLATE MARGIN PROCESSES; DIVERGENT PLATE MARGIN PROCESSES; DRAINAGE BASIN (DRAINAGE SYSTEM); OCEAN BASIN; PLATE TECTONICS; TRANSFORM PLATE MARGIN PROCESSES.

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beaches and shorelines

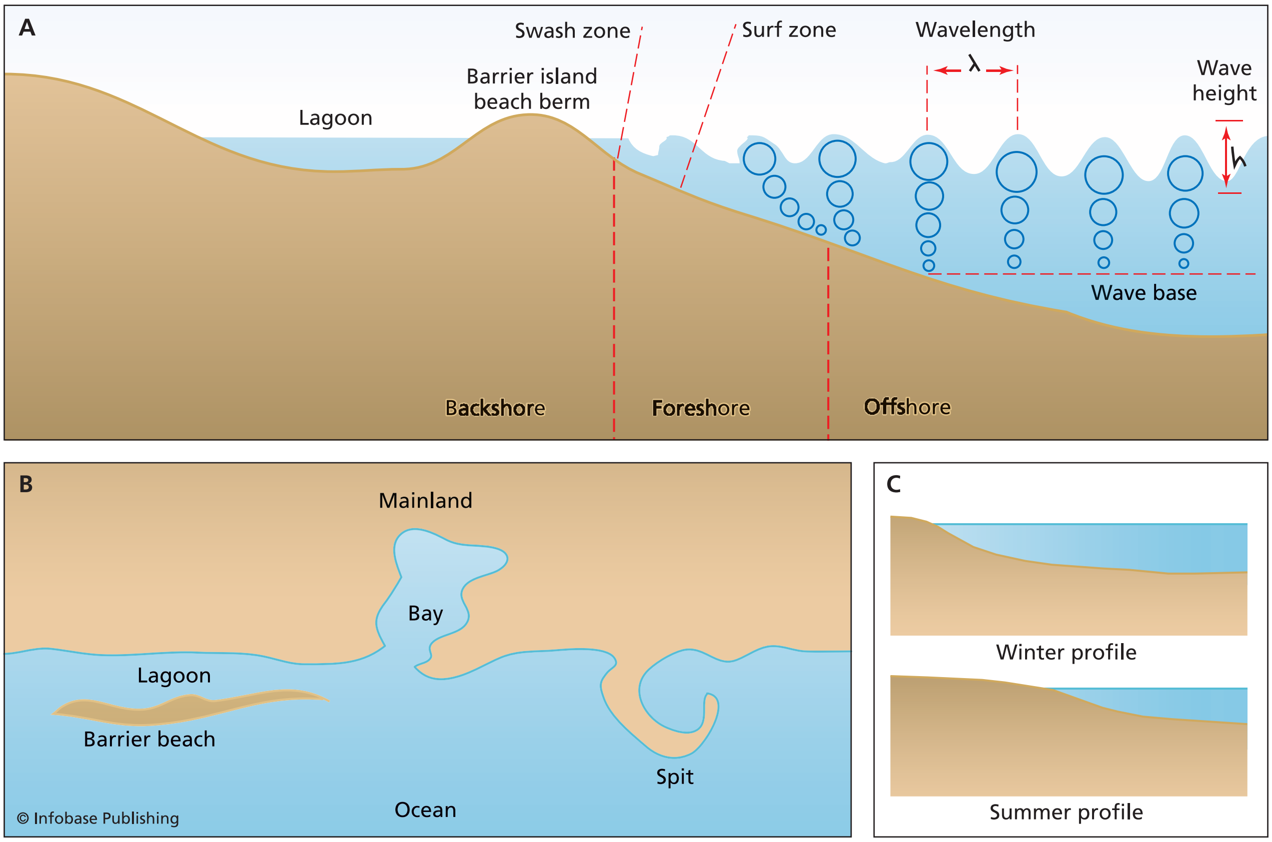
A beach is an accumulation of sediment exposed to wave action along a coastline, whereas the shoreline environment is a more encompassing area including beaches, islands, and near-shore areas that are in some way affected by coastal processes. The beach extends from the limit of the low-tide line to the point inland where the vegetation and landforms change to that typical of the surrounding region. This may be a forest, a cliff, dune, or lagoon. Many beaches merge imperceptibly with grasslands, or forests, whereas others end abruptly at cliffs or other permanent features, including artificial seawalls that have been built in many places in the past century. A beach may occupy bays between headlands, it may form elongate strips attached (or detached, in the cases of barrier islands) to the mainland, or it may form spits that project out into the water. To understand a beach it is necessary also to consider the nearshore environment, the area extending from the low-tide line out across the surf zone. The nearshore environment may include sandbars, typically separated by troughs. The width of nearshore environments is variable, depending on the slope of the seafloor, wave dynamics, and availability of sediment. Most nearshore environments include an inner sandbar located about 100–165 feet (30–50 m) offshore, and another bar about twice as far offshore. The inner bar is often cut by rip channels that allow water that piles up between the bar and beach to escape back to sea, often generating dangerous rip currents that can drag unsuspecting swimmers rapidly out to sea.

In the eastern United States, Florida is known for wide sandy beaches, the Outer Banks of the Carolinas are famous for barrier island beaches, and Maine is well known for its beautiful rocky shorelines. The western coast has many rocky shorelines in Washington, Oregon, and California, whereas the Gulf of Mexico has low relief beaches, barrier islands, and some mangrove-dominated shorelines.

Most sandy beaches develop typical profiles that change through the seasons and include several zones. These are the ridge and runnel, foreshore, backshore, and storm ridge. The ridge and runnel is the most seaward part of the beach, characterized by a small sandbar called a ridge, and a flat-bottom trough called the runnel, and is typically fewer than 30 feet (10 m) wide. The runnel is covered by water at high tide and has many small sand ripples that get extensively burrowed into by worms, crabs, and other beach life.

The foreshore, or beach face, is a flat, seaward-sloping surface that grades seaward into the ridge and runnel, or the intertidal zone if the ridge and runnel are not present. A narrow zone of gravel or broken shells may be present at the small slope-break between the foreshore and the ridge and runnel. The foreshore contains the swash and backwash zone, where waves move sand diagonally up the beach face parallel to the wave incidence direction, and gravity pulls the water and sand directly down the beach face parallel to the slope. This diagonal, then beach-perpendicular motion produces a net transport of sand and water along the beach, known as longshore drift and longshore currents.

The backshore extends from a small ridge and change in slope at the top of the foreshore known as a berm, to the next feature (dune, seawall, forest, lagoon) toward the land. This area is generally flat



(A) Diagram of beach profile showing the major elements from the backshore to offshore; (B) different types of coastal environments, including barrier beaches, bays, and spits; (C) typical beach profiles in summer and winter showing how large winter storms erode the beach and smaller summer waves rebuild the beach

or gently landward sloping. The backshore area is usually dry and above the high-water mark except during large storms, so the backshore area is mainly affected and shaped by wind. Some backshore areas are characterized by multiple berms, and others have none. On gravel beaches, found in high-energy environments, the backshore area may be replaced by a storm ridge marked by a ridge of gravel that may be several to 10 feet (3 m) high. These ridges form because incoming waves have the velocity to move gravels up the beach face, but since these gravels are porous, the water sinks into the gravel before it can drag the gravel back down the beach face, causing its accumulation in a large ridge.

Beaches are highly variable in the width and heights of these various zones. Some beaches are steep, whereas others are flat. Beaches that have flat slopes are said to be dissipative in that they take the energy from waves and gradually dissipate it across the intertidal zone. These types of beaches often have multiple sand bars in the nearshore environment. Reflective beaches are those with steep gradients, and these tend to take much of the wave energy and reflect it back to sea. Reflective beaches do not generally have nearshore bars and are erosive. Dissipative beaches tend to be depositional, as they are actively accreting sediment.

The shape of a beach is largely controlled by the nature of the waves, tides, currents, and, to a lesser extent, wind. Waves move the sediment onshore, and are then transported along the beach face by the longshore currents, and perhaps blown to the backshore by wind. Tides change the areas to which waves direct their energy vertically up and down, bringing the sediment alternatively to different sections of the beach. Out of all these processes, the currents produced by the waves on the beach are the most important. These currents include longshore currents, rip currents, onshore-offshore currents produced in the swash zone, and combined currents.

Beaches are very dynamic environments and are always changing, being eroded and redeposited constantly from day to day and from season to season. They are typically eroded to thin strips, known as storm beaches, by strong winter storms and built up considerably during summer, when storms tend to be less intense. The wide summer beaches are known as accretionary beaches. The processes controlling this

BEAUTY AND THE BEACH: RETHINKING COASTAL LIVING

Civilized societies have built villages, cities, and industrial sites near the sea for thousands of years. Coastal settings offer beauty and commercial convenience but also invite disaster with coastal storms, tsunami, and rising sea levels. In 2004 and 2005 the world witnessed two furious incursions of the sea into heavily populated coastal regions, killing hundreds of thousands of people and causing trillions of dollars in damage. Coastal communities are experiencing early stages of a new incursion, as global sea levels slowly and inexorably rise, increasing the likelihood of additional, even more devastating disasters. These events demand serious reconsideration of priorities about further developing fragile and changing coastlines. Most pressing is a scientific reevaluation of the wisdom of rebuilding areas such as New Orleans, Louisiana, where sinking areas presently far below sea level doom residents to further, more serious disasters and tremendous loss of life. Allowing large, generally poor segments of the population to exist at great risk of death and property loss is socially irresponsible. Reconstruction funds may be better used to relocate large parts of the nation's population that have been displaced by coastal disasters to safer regions.

The year 2005 began with cleanup and recovery efforts from the tragic December 26, 2004, earthquake and tsunami that devastated coastal regions of the Indian Ocean. One of the worst natural disasters of the 21st century unfolded following a magnitude 9.0 earthquake off the northern Sumatra coast. Within minutes of the earthquake a mountain of water 100 feet (30 m) tall was ravaging northern Sumatra, sweeping into coastal villages and resort communities with a fury that crushed all in its path, removing buildings and vegetation, and in many cases eroding shoreline areas down to bedrock. Scenes of destruction and devastation rapidly moved up the coast of nearby Indonesia, then across the Indian Ocean to India and Africa. Buildings, vehicles, trees, boats, and other debris in the water formed projectiles that smashed into other structures at 30 miles (50 km) per hour, leveling all in their path, and killing nearly a quarter million people.

Areas in the United States at greatest risk for tsunamis are along the Pacific coast, including Hawaii, Alaska, Washington, Oregon, and California. Although most tsunamis are generated by earthquakes, others are generated by landslides, volcanic eruptions, meteorite impacts, and possibly gas releases from the deep ocean. Any of these events may happen at any time, in any of the world's oceans, including the Gulf of Mexico, which is prone to tsunamogenic submarine landslides.

Hurricanes Katrina (2005) and Rita (2005) devastated the Gulf Coast, inundating New Orleans with up to 23 feet (7 m) of water. Large sections of the city are uninhabitable, having been destroyed by floods and subsequent decay by contaminated water and toxic mold. The natural human inclination to respond to the disaster is to rebuild the city grander and greater than before, yet years after the disaster fewer than half of the residents of the city have been able to return to their former homes. This is not the most scientifically sound response, and could lead to even greater human catastrophes and financial loss in the future. New Orleans is located on a coastal delta in a basin that is up to 12 feet (3–4 m) below sea level and is sinking at rates of up to an inch (several mm to 2 cm) per year, so that much of the city could be 3–7 feet (1–2 m) farther below sea level by the end of the century. As New Orleans continues to sink, tall levees built to keep the Gulf, Mississippi River, and Lake Pontchartrain out of the city have to be repeatedly raised, and the higher they are built the greater the likelihood of failure and catastrophe.

Flood protection levees that reach 20 feet (6 m) tall built along the Mississippi keep the river level about 25–30 feet (4–5 m) above sea level at New Orleans. If these levees were to be breached, water from the river would quickly fill in

seasonal change are related to the relative amounts of energy in summer and winter storms—summer storms (except for hurricanes) tend to have less energy than winter storms, so they produce waves with relatively short wavelengths and heights. These waves gradually push the offshore and nearshore sands up to the beach face, building the beach throughout the summer. In contrast, winter storms have more energy with longer wavelength, higher amplitude waves. These large waves break on the beach, erode the beach face, and carry the sand seaward, depositing it in the nearshore and offshore environments. In some cases, especially along the rocky Pacific coasts, storms may remove all the sand from beaches, leaving only a rocky bedrock bench behind until the small summer waves can restore the beach. Storm beaches, however, tend to be temporary conditions as the wave energy decreases right after the storms. Even between winter storms the beach may tend to rebuild itself to a wider configuration.

BARRIER ISLANDS

Barrier islands are narrow linear mobile strips of sand up to about 30–50 feet (10–15 m) above sea level, and typically form chains located a few to tens of miles offshore along many passive margins. They the 6–12 foot (2–4 m) deep depression with up to 25 feet (8 m) of water and leave a path of destruction where the torrents of water raged through the city. These levees also channel the sediments that would naturally get deposited on the flood plain and delta far out into the Gulf of Mexico, with the result being that the land surface of the delta south of New Orleans has been sinking below sea level at an alarming rate. A total land area the size of Manhattan is disappearing every year, meaning that New Orleans will be directly on the Gulf by the end of the century. Alarming poststorm assessments of damage from Hurricanes Katrina and Rita push that estimate forward by years.

The projected setting of the city in 2100 is in a bowl up to 30 feet (5 m) below sea level, directly on the hurricane-prone coast, and south of Lake Ponchartrain (by then part of the Gulf). The city will need to be surrounded by 50–100 foot (15–30 m) tall levees that will make the city look like a fish tank submerged off the coast. The levee system will not be able to protect the city from hurricanes any stronger than Katrina. Hurricane storm surges and tsunami could easily initiate catastrophic collapse of any levee system, initiating a major disaster. Advocates of rebuilding are suggesting elevating buildings on stilts or platforms, but forget that the city will be 3–6 meters below sea level by 2090, and that storm surges may reach 30–35 feet (10 m) above sea level. A levee failure in this situation would be catastrophic, with a debris-laden wall of water 45–50 feet (15 m) tall sweeping through the city at 30 miles (50 km) per hour, hitting these buildings-on-stilts with the force of Niagara Falls, and causing a scene of devastation like the Indian Ocean tsunami.

Sea-level rise is rapidly becoming one of the major global hazards that humans must deal with, since most of the world's population lives near the coast in the reach of the rising waters. The current rate of rise of an inch (a couple cm) every 10 years will have enormous consequences. Many of the world's large cities, including New York, Houston, New Orleans, and Washington, D.C., have large areas located within 10–20 feet (a few meters) of sea level. If sea levels rise even a few feet (1 m), many of the city streets will be underwater, not to mention basements, subway lines, and other underground facilities. New Orleans will be the first under, lying a remarkable 10–15 feet (3–5 m) below the projected sea level on the coast at the turn of the next century. At this point governments should not be rebuilding major coastal cities in deep holes along the sinking, hurricane-prone coast. Governments, planners, and scientists must begin to make more sophisticated plans for action during times of rising sea levels. The first step would be to use the reconstruction money for rebuilding New Orleans as a bigger, better, stronger city in a location where it is above sea level, and will last for more than a couple of decades, saving the lives and livelihoods of hundreds of thousands of people.

New Orleans is sinking farther below sea level every year and getting closer to the approaching shoreline. Sea level is rising, and more catastrophic hurricanes and floods are certain to occur in the next 100 years. Americans must decide whether to spend hundreds of billions of tax dollars to rebuild a city with historic and emotional roots where it will be destroyed again, or to move the bulk of the city to a safer location before subsidence increases and another disaster strikes. The costs of either decision will be enormous. The latter makes more sense and will eventually be inevitable. The city could be moved in the slump following the destruction by Hurricane Katrina, saving lives, or residents could wait until an unexpected category five superhurricane makes a direct hit and kills hundreds of thousands of people. Katrina was a warning, New Orleans is sinking below sea level, and it is time to move to high and dry ground.

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are separated from the mainland by the back-barrier region, which is typically occupied by lagoons, shallow bays, estuaries, or marshes. Barriers are built by vertical accumulation of sand from waves and wind action. Barrier islands are so named because they form a natural protection of the shoreline from the forces of waves, tsunami, tides, and currents from the main ocean. Many barrier islands have become heavily developed, however, as they offer beautiful beaches and resort-style living. The development of barrier islands is one of the most hazardous trends in coastal zones, since barriers are simply mobile strips of sand that move in response to changing sea levels, storms, coastal currents, and tides. Storms are capable of moving the entire sandy substrate out from underneath tall buildings.

The size of barrier islands ranges from narrow and discontinuous strips of sand that may be only a few hundred feet wide, to large islands that extend many miles in width and length. The width and length is determined by the amount of sediment available, as well as a balance between wave and tidal energy. Most barriers are built of sand, either left over from glaciations, as in New England, eroded from coastal cliffs, or deposited by rivers along deltas such as at the end of the Mississippi River in the Gulf

Photo of waves crashing on beach *(Stephanie Coffman, Shutterstock, Inc.)*

of Mexico. Barrier island systems need to be discontinuous, to allow water from tidal changes to escape back to sea along systems of tidal inlets.

Subenvironments of barriers are broadly similar to those of beaches; they include the beach, barrier interior, and landward interior. The beach face of a barrier is the most dynamic part of the island, absorbing energy from waves and tides, and responding much as beaches on the mainland do. The backside of the beach on many barrier islands is marked by a long frontal or foredune ridge, followed landward by secondary dunes. Barrier islands that have grown landward with time may be marked by a series of linear ridges that mark the former positions of the shoreline and foredune ridges, separated by low areas called swales. The landward margins of many barriers merge gradually into mud flats, or salt marshes, or may open into lagoons, bays, or tidal creeks.

About 15 percent of the world's coastlines have barrier islands offshore, with most located along passive-margin continental shelves, which have shallow slopes and a large supply of sediment available to build the barriers. In the United States the eastern seaboard and Gulf of Mexico exhibit the greatest development of barrier island systems. It seems that areas with low tidal ranges in low to middle climate zones have the most extensively developed barrier systems.

Barrier systems are of several types. Barrier spits are attached to the mainland at one end and terminate in a bay or the open ocean on the other end. They are most common along active tectonic coasts, although Cape Cod in Massachusetts is one of the better-known examples of a spit formed along a passive continental margin. Some spits have ridges of sand that curve around the end of the spit that terminates in the sea, reflecting its growth. These are known as recurved spits. Sandy Hook, at the northern end of the New Jersey coast, is a recurved spit. Spits form as longshore currents carry sediment along a coastline, and the coastline makes a bend into a bay. In many cases the currents that carry the sand continue straight and carry the sediment offshore, depositing it in a spit that juts out from the mouth of the bay. Many other subcategories of spits are known and classified according to specific shape. Some, known as tombolos, may connect offshore islands with the mainland, whereas others have cuspate forms or jut outward into the open water.

In some cases barriers grow completely across a bay and seal off the water inside it from the ocean. These are known as welded barriers and are most common along rocky coasts such as in New England and Alaska. Welded barriers seem also to form preferentially where tidal energy is low, as this prevents the tides from creating tidal channels that allow salty water to circulate into the bay. Some also form during onshore migration of barriers during times of sea-level rise, when the barrier sands get moved into progressively narrowing bays as they are forced to move inland. Since they are cut off from the ocean, bays that form behind welded barriers tend to be brackish or even filled with freshwater.

Barriers form by a variety of different mechanisms in different settings, but the most common mechanisms include the growth and accretion of spits that become breached during storms, growth as offshore sandbars, and as submergence of former islands during times of sea-level rise. Barriers are constantly moving and respond to storms, currents, waves, and sea-level rise by changing their position and shape. Barriers moving onshore are known as retrograding barriers; they move by a process of rolling over, where sand on the outer beach face is moved to the backshore, then overrun by the next sand from the beach face. A continuation of this process leads the barrier to roll over itself as it migrates onshore. Prograding barriers are building themselves seaward, generally through a large sediment supply, whereas aggrading barriers are simply growing upward in place as sea levels rise.

COASTAL DUNES

Many coastal areas have well-developed sand dunes in the backshore area, some of which reach heights of several tens or even hundreds of feet (tens of meters). The presence or absence of dunes, and their shape and height, is mostly controlled by the amount of sediment supply available, although wind strength and type and distribution of vegetation also play significant roles. Dunes are fragile ecosystems that can easily be changed by disturbing the vegetation or beach dynamics, yet their importance is paramount to protecting inland areas from storm waves and surges, tsunami, and other hazards from the ocean.

Most coastal dunes are of the linear type, known as foredunes, which form elongate ridges parallel to the beach just landward of the foreshore. In some cases numerous foredunes are present, with the ones closest to land being the oldest and the younger ones forming progressively seaward of these older dunes.

Sand dunes in the backbeach area are built by the windblown accumulation of sand derived from the foreshore area. The sands may grow far into the backshore environment, in some cases extending miles inland if not obstructed by vegetation, cliffs, or constructions such as buildings or seawalls. Vegetation is extremely effective at stabilizing mobile sand, and many examples of sand being trapped by plants are visible on beaches of the world.

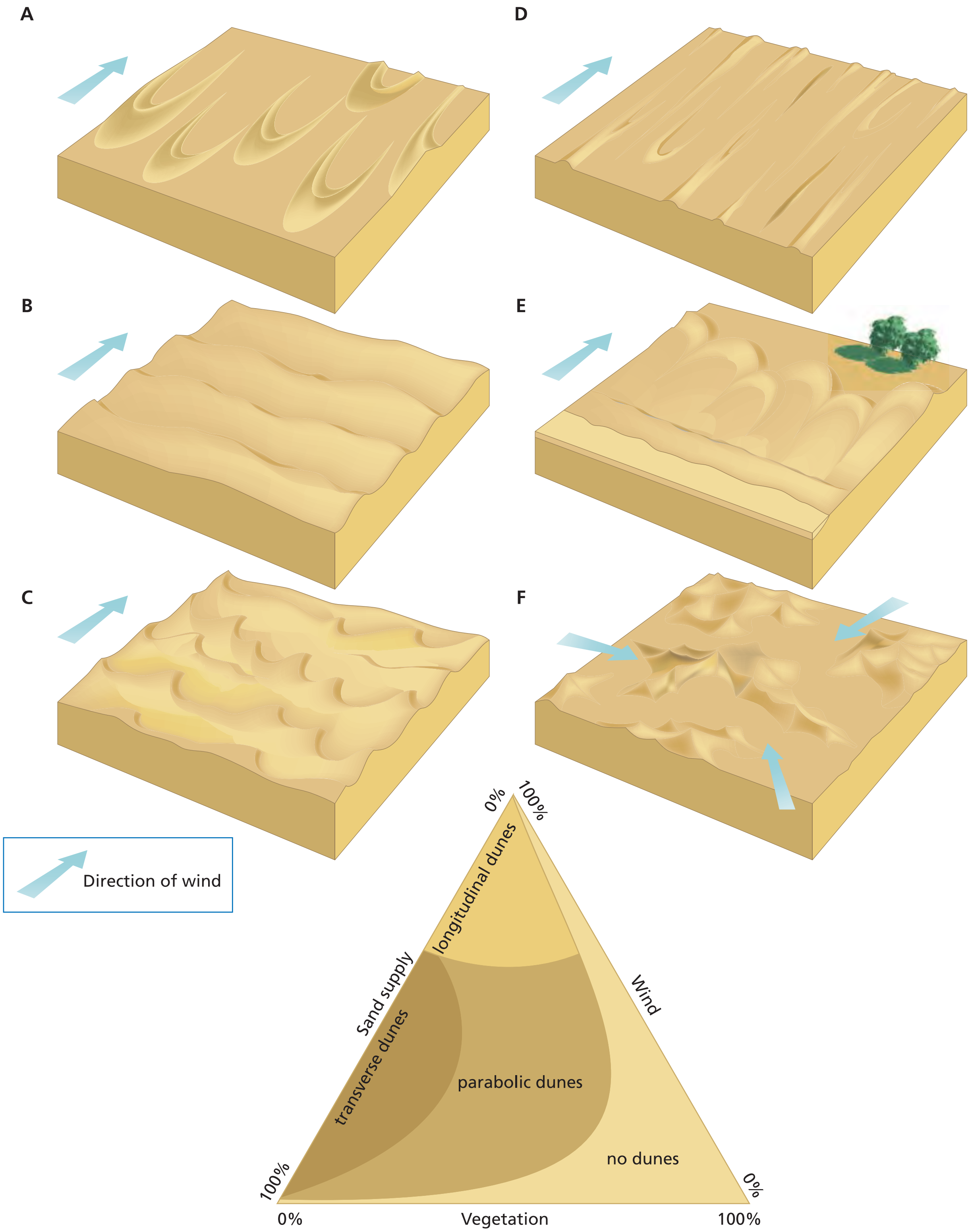
Dunes are built by the slow accumulation of sand moved by wind, but may be rapidly eroded by storm surges and wave attack when the sea surface is elevated on storm surges. A single storm can remove years of dune growth in a few hours, transporting the dune sand offshore or along shore. Examples of this process were all too clear from Hurricanes Katrina in Louisiana and Mississippi in 2005 and Ike along the Texas coast in 2008. Likewise, tsunamis can remove entire dune fields in a single devastating event, as seen in many places during the Indian Ocean tsunami of December 2004. Rising sea levels pose a huge threat to many existing coastal dune fields, since a rise in sea level of one foot (0.3 m) on flat terrain can be equated with a 100-foot (305 m) landward migration of the shoreline, and the removal of the dune field from one location to an area farther inland, or to its complete elimination.

COASTAL LAGOONS

Lagoons are a special, rather rare class of restricted coastal bays that are separated from the ocean by an efficient barrier that blocks any tidal influx, and they do not have significant freshwater influx from the mainland. Water enters lagoons mainly from rainfall and occasional storm wash-over. Evaporation from the lagoon causes their waters to have elevated salinity and distinctive environments and biota.

Most lagoons are elongate parallel to the coast and separated from the ocean by a barrier island or in some cases by a reef. They are most common in dry or near-desert climates, since freshwater runoff needs to be very limited to maintain lagoon conditions. Lagoons are therefore common along coasts including the Persian Gulf, North Africa, southeast Africa, Australia, Texas, Mexico, and southern Brazil.

Many lagoons show large seasonal changes in salinity, with nearly fresh conditions during rainy seasons and extremely salty conditions as the waters evaporate and even dry up in the dry seasons. Normal marine and estuarine organisms cannot tolerate such wide variations in salinity, so typically large numbers of a relatively few specialized species of organisms are found in lagoons. Some species of fish, such as the killifish, can regulate the salinity in their bodies to match that of the outside waters, so they are well suited for the lagoon environment. Certain species of gastropods (snails) are also very tolerant to variations in salinity, and are found in large quantities in some lagoons.



Block diagram of types of dunes including (A) barchan, (B) transverse, (C) barchanoid, (D) linear, (E) parabolic, and (F) star. Graph (triangular) illustrates which types of dunes form under different conditions of wind, sand supply, and vegetative cover.

As the water in lagoons evaporates in summer months, it deposits chemical sediments known as evaporates and carbonates. These typically include a sequence of minerals from aragonite to calcite to gypsum to halite. Many ancient lagoon environments are recognized by the presence of this repeating sequence of evaporate and carbonate minerals in the rock record.

Lagoons are not significantly influenced by waves or tides, and are dominated by effects of the wind. Winds can induce circulation in lagoons or even waves during windstorms. Small wind tides in lagoons may transport more water to one side of the lagoon, and deposit fine-grained sediments on this one side as the waters retreat when the wind dies out. During large ocean storms tidal surges may overtop the barrier to the lagoon, bringing a surge of seawater and sediment into the lagoon. During storms, and during the daily sea breeze cycle, sand from the beach and coastal dunes can be transported into lagoons. This can be a major contributor to sediment accumulation in some lagoons, and in some examples sand dunes from the beach are moving landward into lagoons, migrating over lagoonal sediments and vegetation.

Sediments deposited in lagoons include layers of chemical sediments that precipitated from the water as it evaporated, leaving behind the elements initially dissolved in the water as sedimentary layers. These sediments are most commonly fine-grained, clay-sized calcite and aragonite, and micrite, a form of carbonate mud. Many lagoons are covered by mucky micrite layers that have green slimy microorganisms known as cyanobacteria, or blue-green algae, growing along the edges of the lagoon in the mud and forming matlike pads surrounding the central, water-filled part of the lagoon. Many times these mudflats and algal pads are dried out and cracked by the Sun, forming thin flakes that can be blown around by the wind. Lagoons also have sediments such as sand grains carried by the wind, and the skeletal and other remains of the organisms that lived in the lagoon. Sand washed into lagoons from storms often forms small, fan-shaped bodies known as wash-over fans that cover parts of the lagoon on its seaward side.

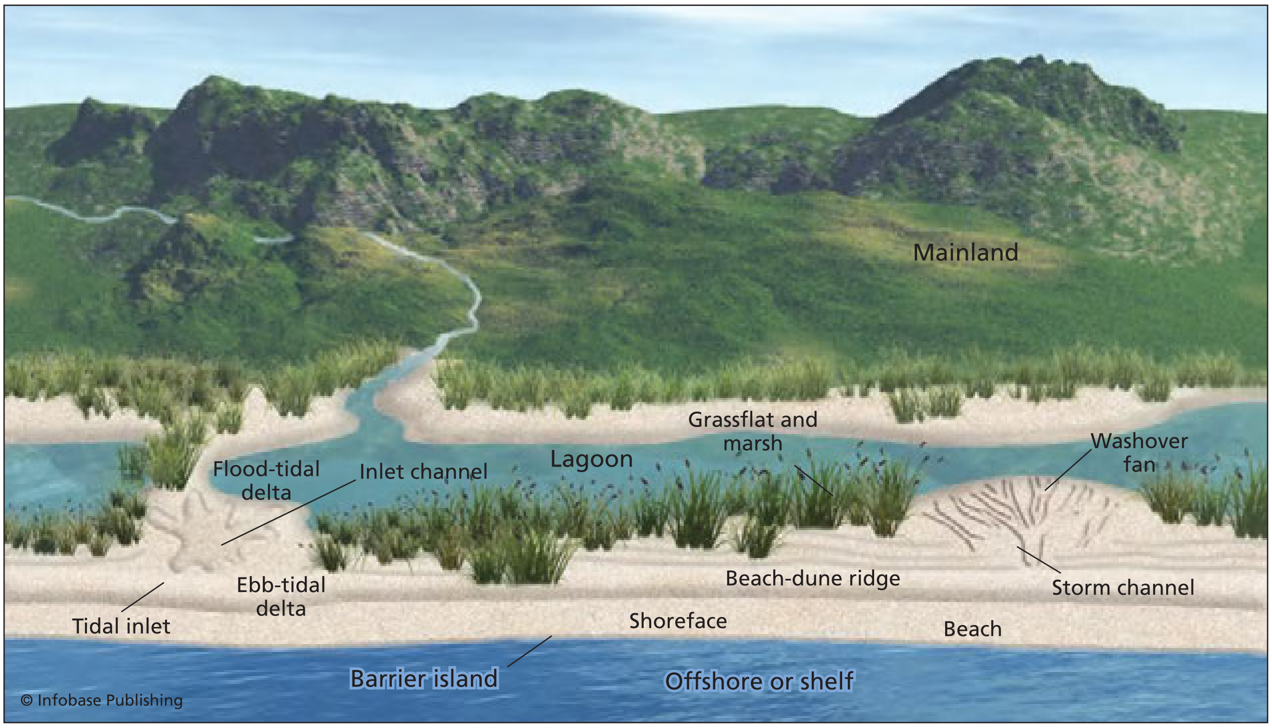
TIDAL INLETS

Tidal inlets are breaks in barrier island systems that allow water, nutrients, organisms, ships, and people easy access and exchange between the high-energy open ocean and the low-energy back-barrier environment consisting of bays, lagoons, tidal marshes, and creeks. Most tidal inlets are within barrier island systems, but others may separate barrier islands from rocky or glacial headlands. Tidal inlets are extremely important for navigation between sheltered ports on the back-barrier bays and the open ocean; thus they are the sites of many coastal modifications such as jetties, breakwaters, and dredged channels to keep the channels stable and open.

Strong tidal currents move water into and out of tidal inlets as the tides wax and wane, and also carry out of the channel large amounts of sediment brought in by waves and long shore transport. Never try to swim in a tidal inlet. As tides rise on the ocean side of tidal inlets the water rises faster than on the inside of the inlet, since the inlet is narrow and it takes a long time for the water to move into the restricted environment behind the barrier. The difference in elevation causes the water to flow into the inlet with a strong current, called a flood-tidal current. As the tide falls outside the inlet, the reverse happens—as the tide falls quickly on the outside of the barrier, the sea surface is higher inside the inlet and a strong current known as an ebb-tidal current then flows out of the inlet, returning the water to the ocean. Considering the amount of time that it takes for water to flow into and out of tidal inlets, it is apparent that times of high and low tide may be considerably different on the two sides of barrier systems connected by tidal inlets.

The sides of tidal inlets are often marked by curved sand ridges of recurved spits, formed as waves are refracted into the barrier and push the sand into ridges. The strongest currents in tidal inlets are found where the inlet is the narrowest, a place with the deepest water called the inlet throat. Water rushes at high velocity into and out of this throat, carrying sand into and out of the back-barrier environment. Since the velocity of the water decreases after it passes through the throat, large lobes and sheets of sand are typically deposited as tidal deltas on both the inside and the outside of tidal inlets. The delta deposited by the incoming (flood) tide on the inside or landward side of the inlet is known as a flood-tidal delta, whereas the delta deposited on the outside of the inlet by the ebb tide is known as an ebb-tidal delta.

Tidal inlets form by a variety of mechanisms. The most common is during the formation and evolution of barrier systems along coastal platforms on passive margins, where barrier islands emerged as glaciers retreated and sea levels rose onto the continental shelves in Holocene times. Sea levels rose more slowly about 5,000 years ago, and enhanced coastal erosion provided abundant sand to create the barrier island systems. Continued rising sea levels plus diminished sediment supplies and the many modifications of the shoreline by humans has led to increased erosion along much of the world's coastlines. With



Sketch showing features of a barrier island, tidal inlet, and lagoon coastal system. Note the positions of the small deltas on either side of the tidal inlet, the coastal march, and beach-dune ridge. *(modeled after R. Davis and D. Fitzgerald).*

this trend many barriers have been breached or cut through during storms. Typically this happens when an incoming storm erodes the foredune ridge, and waves top the barrier island, washing sand into the back barrier region, often making a shallow channel through the barrier. As the storm and elevated tides recede, the water in the back barrier bay, lagoon, or tidal marsh is left high, then begins to escape quickly through the new shallow opening, deepening it rapidly. If the tides can continue to keep this channel open, a new tidal inlet is established. Many tidal inlets along the Outer Banks barrier islands of North Carolina have formed in this way. Any homes or roads that were in the way are gone.

Tidal inlets may also form by longshore currents, building a spit across a bay or drowned river valley. As the spit grows across an open bay, the area open to the sea gradually becomes narrower until it begins to host strong tidal currents, when it becomes deep and reaches an equilibrium between the amount of sediment transported to the inlet by longshore drift and the amount of sand moved out of the inlet by tidal currents and waves.

INTERTIDAL FLATS

Many coastlines have flat areas within the tidal range sheltered from waves, dominated by mud, and devoid of vegetation that are accumulating sediment, known as intertidal (or just tidal) flats. The width of tidal flats depends on the tidal range and the shape and morphology of the coastline or bay where they are located. Some large bays with large tidal ranges, such as the Bay of Fundy in eastern Canada, are dominated by tidal flats. Tidal flats are typically flat areas cut by many channels and dominated by mud and sandy sediment. Many may have layers of shell debris and ecosystems of organisms specially adapted to this environment. They are alternately covered at high water and exposed to the atmosphere at low tide.

The sand, mud, and shell fragment layers that most tidal flats comprise are distributed in ways that reflect the distribution of energy in this environment. Sands are typically located near the base of the intertidal zone where energy from tides is the highest, and these sands gradually merge with and then give way to muds toward the upper parts of the zone, and away from the ocean. At any given location within the tidal flats the sediments tend to be rather uniform, because of the similar conditions that persist and repeat at any given location.

Modern tidal flat environments are inhabited by a variety of organisms specially adapted to this harsh environment, including specialized snails, worms, amphipods, oysters, mussels, and other bivalves. Many of these organisms survive by burrowing into the mud for protection; in doing so they destroy the fine-scale layering in the mud by a process called bioturbation. The mud in many tidal flats is also inhabited by microscopic filamentous cyanobacteria (commonly called blue-green algae) that produce slimy mats that cover many mud surfaces and hold the mud particles together during the ebb and flow of the tides. These mucaceous mats also trap mud and other sediments, helping to build up the sedimentary accumulation in these environments.

Tidal flats often expose sediments in which the sedimentary particles are arranged in specific, peculiar, and repeating forms known as sedimentary structures. Familiar types of sedimentary structures include sedimentary layers; ripples, produced by currents moving the sedimentary particles as sets of small waves; mega-ripples, large ripples formed by unusually strong currents; mudcracks, produced by muddy sediments being dried by the Sun and shrinking and cracking; and other structures produced by organisms. These latter structures include burrows from worms, bivalves, and other organisms, trails, and footprints.

Most tidal flats are cut by a network of tidal channels that may contain water even at low tides. These form a network of small to large channels but differ from normal streams in that they carry water in different directions with the ebb and flood of the tides. As the tide rises into tidal flats strong currents that range up to several feet (1 m) per second bring the tidal wave through these channels, moving sediments throughout the flats. Tidal flats tend to build themselves slowly seaward, out from the bays or estuaries that they initially grow around. They may eventually fill in the bays and estuaries up to the sand dunes or berm in the back-beach area or coastal barrier. Most tidal flats are not significantly affected by waves. Exceptionally large flats, however, such as the Wadden Sea area of the North Sea on Germany's coast are significantly affected by waves for several hours of each high-tide stand.

COASTAL WETLANDS AND MARSHES

Many bays, estuaries, and coastal tidal flats are bordered inland by a vegetated intertidal area containing grasses or shrublike mangrove swamps. Mangroves do not tolerate freezing conditions so are found only at low latitudes, whereas salt marshes are found at all latitudes. These coastal wetlands or salt marshes host a range of water salinities, from salty and brackish to nearly fresh. As estuaries age or mature, they tend to become progressively filled in first by tidal flats, then by salt marshes or coastal wetlands. Thus the degree to which estuaries are filled in can indicate the state of their maturity.

Salt marshes form on the upper part of the intertidal zone where organic rich sediments are rarely disturbed by tides, providing a stable environment for grasses to take root. The low marsh area is defined as the part of the marsh that ranges from the beginning of vegetation to the least mean high tide. The high marsh extends from the mean high tide up to the limit of tidal influence. Different genera and species of grass form at different latitudes and on different continents, but in North America high parts of salt marshes are dominated by Juncus grasses, known also as needle- or black-rush, which can be 5 to 6 feet (2 m) tall, with sharp, pointed ends. Low parts of salt marshes tend to be dominated by dense growths of knee-high Spartina grasses.

Salt marshes must grow upward to keep up with rising sea levels. To do this they accumulate sediments derived from storm floods moving sediment inland from the beach environment, from river floods bringing in sediment from the mainland, and from the accumulation of organic material that grew and lived in the salt marshes. When plants in salt marshes are suddenly covered by sediment from storms or floods, they quickly recover by growing up through the new sediment, thereby allowing the marsh to survive and grow upward. Some salt marshes grow upward so efficiently that they raise themselves above tidal influence and eventually become a freshwater woodland environment. With the increasing rate of sea-level rise predicted for the next century, however, many scientists are concerned that sea level will start to rise faster than marsh sedimentation can keep pace with it. This problem is particularly exacerbated in places where the normal supply of river and flood sediments is cut off, for instance, by levees along rivers. If this happens, many of the fragile and environmentally unique coastal marsh settings will disappear. Marshes are among the most productive of all environments on Earth; they serve as nurseries for many organisms and are large producers of oxygen through photosynthesis. The disappearance of coastal marshes is already happening at an alarming rate in places such as the Mississippi River delta, where coastal subsidence, loss of delta replenishment, together with sea-level rise leads to more than 0.39 inches (1 cm) of relative sea-level rise each year. Salt marshes are disappearing at an alarming rate along the Mississippi River delta, as discussed in a later chapter.

Many coastal marshes in low latitudes are covered with dense mangrove tidal forest ecosystems, known also as mangals. These have fresh to brackish water and are under tidal influence. Mangrove stands have proven to be extremely effective protective barriers against invaders from the sea, including hostile armies, storm surges, and tsunamis. The destruction of many coastal mangrove forests in recent years has proven catastrophic to some regions, such as areas inundated by the 2004 Indian Ocean tsunami that were once protected by mangroves. Many local governments removed the mangroves to facilitate development and shrimp farming, but when the tsunami hit, it swept far inland in areas without mangroves, and was effectively stopped in places where the mangroves were still undisturbed. There are many examples of places where mangrove-dominated coasts have withstood direct hits from hurricanes and storm surges, yet protected the coastline to the extent that there was little detectable change after the storm.

Several dozen or more types of mangroves are known, occurring on many coasts of North America, Africa, South America, India, Southeast Asia, and elsewhere around the Pacific. Mangroves prefer protected, low-energy coasts such as estuaries, lagoons, and back-barrier areas. Mangroves develop extensive root systems and propagate by dropping seeds into the water, where they take root and spread. Mangrove stands have also been known to be uprooted by storms, float to another location, and take root in the new setting.

The extensive root network of mangrove stands slows many tidal currents and reduces wave energy by a factor of 10, forming lower-energy conditions inside the mangrove forest. These lower-energy conditions favor the deposition of sediment, enhancing seaward growth of the mangrove forest.

DELTAS

Deltas are low flat deposits of alluvium at the mouths of streams and rivers that form broad triangular- or irregular-shaped areas that extend into bays, oceans, or lakes. They are typically crossed by many distributaries from the main river and may extend for a considerable distance underwater. When a stream enters the relatively still water of a lake or the ocean, its velocity and its capacity to hold sediment drop suddenly. Thus the stream dumps its sediment load there, and the resulting deposit is known as a delta. The term *delta* was first used for these deposits by Herodotus in the fifth century B.C.E., for the triangular-shaped alluvial deposits at the mouth of the Nile River. The stream first drops the coarsest material, then progressively finer material further out, forming a distinctive sedimentary deposit. In a study of several small deltas in ancient Lake Bonneville in Utah, Nevada, and Idaho, Grover Karl Gilbert in 1890 recognized that the deposition of finer-grained material farther away from the shoreline also created a distinctive vertical sequence in delta deposits. The resulting foreset layer is thus graded from coarse nearshore to fine offshore. The bottomset layer consists of the finest material, deposited far out. As this material continues to build outward, the stream must extend its length and forms new deposits, known as topset layers, on top of all this. Topset beds may include a variety of subenvironments, both subaqueous and subaerial, formed as the delta progrades seaward.

Most of the world's large rivers such as the Mississippi, the Nile, and the Ganges, have built enormous deltas at their mouths, yet all of these are different in detail. Deltas may have various shapes and sizes or may even be completely removed, depending on the relative amounts of sediment deposited by the stream, the erosive power of waves and tides, the climate, and the tectonic stability of the coastal region. The distributaries and main channel of the rivers forming deltas typically move to find the shortest route to the sea, and this causes the shifting of the active locus of deposition on deltas. Inactive areas, which may form lobes or just parts of the delta, typically subside and are reworked by tidal currents and waves. High-constructive deltas form where the fluvial transport dominates the energy balance on the delta. These deltas are typically elongate, such as the modern delta at the mouth of the Mississippi, shaped like a bird's foot, or they may be lobate, such as the older Holocene lobes of the Mississippi that have now largely subsided below sea level.

High-destructive deltas form where the tidal and wave energy is high and much of the fluvial sediment gets reworked before it is finally deposited. In wave-dominated high-destructive deltas sediment typically accumulates as arcuate barriers near the mouth of the river. Examples of wave-dominated deltas include the Nile and the Rhône deltas. In tide-dominated high-destructive deltas, tides rework the sediment into linear bars that radiate from the mouth of the river, with sands on the outer part of the delta sheltering a lower-energy area of mud and silt deposition inland from the segmented bars. Examples of tide-dominated deltas include the Ganges and the Kikari and Fly River deltas in the Gulf of Papua, New Guinea. Other rivers drain into the sea in places where the tidal and wave current is so strong that these systems completely overwhelm the fluvial deposition, removing most of the delta. The Orinoco River in South America has had its sediment deposits transported southward along the South American coast, with no real delta formed at the mouth of the river.

Where a coarse sediment load of an alluvial fan dumps its load in a delta, the deposit is known as a fan-delta. Braid-deltas are formed when braided streams meet local base level and deposit their coarse-grained load.

Deltas create unique, diverse environments where fresh and saltwater ecosystems meet, and swamps, beaches, and shallow marine settings are highly varied. Deltas also form some of the world's greatest hydrocarbon fields, as the muds and carbonates make good source rocks and the sands make excellent trap rocks.

GLACIATED COASTS

Glaciated and recently deglaciated coastlines offer a variety of environments that are significantly different from other coastal features so far discussed. Some coastlines, such as many in Antarctica, Greenland, and Alaska, have active glaciers that reach the sea, whereas other coasts, such as from New England northward into Canada, Scandinavia, and parts of the Far East have recently been deglaciated (within the past 18,000 years).

The primary effects of glaciers on coastlines include the carving out of wide U-shaped glacial valleys and erosion of loose material overlying bedrock, the deposition of huge quantities of sediment especially near the termini of glaciers, and lowering of global sea levels during periods of widespread glaciation. In addition, many coastal areas that had thick ice sheets on them were depressed by the weight of the glaciers, and have been slowly rebounding upward since the weight of the glaciers was removed. This glacial rebound causes coastal features to move seaward and former beaches and coastlines to be uplifted.

When glaciers move across the land surface, they can erode bedrock by a combination of grinding and abrasion, plucking material away from the bedrock, and ice wedging where water penetrates cracks, expands as it freezes, and pushes pieces of bedrock away from its base. The material removed from the bedrock and overburden is then transported with the glacier to its end point, often at the coast, where it may be deposited as a pile of gravel, sand, and boulders known as a glacial moraine. Some glacial moraines are relatively small and outline places where individual glaciers flowed out of valleys and ended at the sea. These form where the glaciers were relatively small and were confined to valleys. Other glacial moraines are huge, and mark places where continental ice sheets made their farthest movement southward, depositing vast piles of sand and gravel at their terminus. On the eastern seaboard of the United States, New York's Long Island and Massachusetts's Cape Cod, Martha's Vineyard, and Nantucket Island represent the complex terminal moraine from the Pleistocene ice sheets. In places like New England that were covered by large continental ice sheets, the glaciers tended to scour the surface to the bedrock, leaving behind irregular and rocky coasts characterized by promontories and embayments, islands, but only rare sandy beaches.

Depositional features on deglaciated coasts are varied. *Glacial drift* is a general term for all sediment deposited directly by glaciers, or by glacial meltwater in streams, lakes, and the sea. Till is glacial drift that was deposited directly by the ice. It is a nonsorted random mixture of rock fragments. Glacial marine drift is sediment deposited on the seafloor from floating ice shelves or bergs, and may include many isolated pebbles or boulders that were initially trapped in glaciers on land, then floated in icebergs that calved off from tidewater glaciers. These rocks melted out while over open water, and fell into the sediment on the sea bottom. These isolated dropstones are often one of the hallmarks of ancient glaciation in rock layers that geologists find in the rock record. Stratified drift is deposited by meltwater and may include a range of sizes, deposited in different fluvial or lacustrine environments.

Terminal or end moraines are ridgelike accumulations of drift deposited at the farthest point of travel of a glacier's terminus. Terminal moraines may be found as depositional landforms at the bases of mountain or valley glaciers marking the locations of the farthest advance of that particular glacier, or may be more regional in extent, marking the farthest advance of a continental ice sheet. There are several different categories of terminal moraines, some related to the farthest advance during a particular glacial stage, and others referring to the farthest advance of a group of or all glacial stages in a region. Continental terminal moraines are typically succeeded poleward by a series of recessional moraines marking temporary stops in the glacial retreat or even short advances during the retreat. They may also mark the boundary between a glacial outwash terrain and a knob and kettle or hummocky terrain toward more poleward latitudes from the moraine. The knob and kettle terrain is characterized by knobs of outwash gravels and sand separated by depressions filled with finer material. Many of these kettle holes were formed when large blocks of ice were left by the retreating glacier, and the ice blocks melted later, leaving large pits where the ice once was. Kettle holes are typically filled with lakes; many regions characterized by many small lakes have a recessional kettle hole origin.

Glacial erratics are glacially deposited rock fragments with compositions different from underlying rocks. In many cases the erratics are composed of rock types that do not occur in the area they are resting in, but are found only hundreds or even thousands of miles away. Many glacial erratics in the northern part of the United States can be shown to have come from parts of Canada. Sediment deposited by streams washing out of glacial moraines, known as outwash, is typically deposited by braided streams. Many of these glacial outwash braided streams form on broad plains known as outwash plains. When glaciers retreat, the load is diminished, and a series of outwash terraces may form.

Drumlins are teardrop-shaped accumulations of till that are up to about 150 feet (50 m) in height, and tend to occur in groups of many drumlins. These have a steep side that faces in the direction that the glacier advanced from and a back side with a more gentle slope. Drumlins are thought to form beneath ice sheets and record the direction of movement of the glacier. Drumlin coasts are found on the eastern side of Nova Scotia and in Massachusetts Bay, including many in Boston Harbor. A final common depositional landform of glaciers found on many coasts are eskers, elongate ridges of sands and gravel that may extend many miles but be only a few tens of feet (several m) wide. These represent the paths of meltwater streams that flowed inside and underneath the glaciers, depositing the sand and gravel in the stream bed, which got left behind as the glacier retreated.

Coastlines that were mountainous when the glaciers advanced had their valleys deepened by the glaciers carving out their floors and sides, creating fjords. Fjords are steep-sided glacial valleys that open to the sea. Southern Alaska has numerous fjords that have active tidewater glaciers in them, which are now experiencing a phase of rapid retreat. The Hudson River valley and Palisades just north of New York City comprise a fjord formed in the Pleistocene, and many fjords are found in Scandinavia, New Zealand, Greenland, Chile, and Antarctica.

ROCKY COASTS

Rocky coastlines are most common along many convergent tectonic plate boundaries and on volcanic islands, but may also be found on recently deglaciated coasts and along other uplifted coasts such as southern Africa and recently uplifted coasts such as along the Red Sea. Rocky coasts are the most common type of coastline in the world, forming on the order of 75 percent of the world's coasts. The morphology of rocky coastlines is determined mainly by the type of rock, its internal structure and tectonic setting, as well as the physical, chemical, and biological processes operating on the coastline. Coastlines with mountains and steep slopes under the sea tend to have large waves, since little of the wave energy is dissipated by shallow water as the waves approach. These large waves erode the coast and also transport any sand that tends to accumulate offshore, so it is rare to find sandy beaches on steep, rocky coastlines. Some tropical islands have exposures of jagged limestone along their coastlines. Much of this limestone formed as shallow water mud and reefs, and was exposed above sea level when sea levels fell during the Pleistocene.

The rates of geological processes and change along rocky coastlines are much slower than along sandy beaches, so it is often difficult to notice change over individual lifetimes. Rocky coastlines are experiencing erosion over geological time periods, however, through a combination of waves, rain, ice wedging during the freeze-thaw cycle, and chemical and biological processes. Waves that continuously pound on rocky coastlines are the most effective erosive agents, slowly wearing down the rock and, in some cases, quarrying away large boulders. When waves carry sand and smaller rocks, these particles are thrown against the coastal rocks, causing significant abrasion and erosion. Abraded rock surfaces tend to be smooth, whereas those eroded by wave quarrying are irregular.

In higher latitudes subject to the freeze-thaw cycle, water often gets trapped in cracks and joints in the rock and then freezes. Since water expands by 9 percent when it freezes, this creates large stresses on the rock around the crack, often enough to expand the crack and eventually contribute to causing blocks of rock to separate from the main rocky coast and become a boulder.

Biological processes also contribute to the erosion of rocks along rocky coasts. Microscopic blue-green algae burrow into limestone, using the calcium carbonate ($CaCO_3$) as a nutrition source and causing the limestone to be more easily weathered away, a fraction of an inch (mm) at a time. Other organisms, such as sea urchins, abalone, chitons, and other invertebrates, bore into rocky substrate, slowly eroding the coast. Rocks along the coast are also subject to chemical weathering, like other rocks in other environments. Limestones may be dissolved by acid rain, and feldspars in granites and other rocks may be converted by hydrolysis into soft, easily eroded clay.

The relative strength of these processes is determined by several factors, including rock type, climate, wave energy, rock structure, tidal range, and sea level. Soft rocks such as sandstones are easily eroded, whereas granites weather much more slowly and typically form headlands along rocky coasts. Highly fractured rocks tend to break and erode faster, especially in climates with a significant freeze-thaw cycle. In humid wet climates chemical erosion may be more important than the freeze-thaw cycle. Wave height and energy is important, as waves exert their greatest erosive power at just above the mean high-water level and are very effective at slowly removing rocks, seawalls, and other structures, particularly in places where sandy beaches are absent. Sandy beaches absorb wave energy, so when beaches are absent the waves are much more erosive. Areas with small tidal ranges tend to focus the wave energy on a small area, whereas areas with large tidal ranges tend to change the area being attacked by waves. Thus tides and relative sea level also influence the effectiveness of waves in eroding the coast.

Many rocky coasts are bordered by steep cliffs, many of which are experiencing active erosion. The erosion is a function of waves' undercutting the base of the cliffs and oversteepening the slopes, which then collapse to form a pile of boulders that are then broken down by wave action. On volcanic islands, such as Hawaii and Cape Verde, some large, amphitheater-shaped cliffs were formed by giant landslides when large sections of these islands slumped into the adjacent ocean, creating the cliffs and generating tsunamis. In contrast, cliffs of unconsolidated gravels and sand attempt to recover to the angle of repose by rain water erosion or slumping from the top of the cliff. This erosion can be dramatic, with many tens of feet removed during single storms. The material eroded from the cliffs replenished the beaches, and without the erosion the beaches would not exist. Coarser material is left behind as it cannot be transported by the waves or tidal currents while the finer-grained material is carried out to sea. The remaining coarse-grained deposits typically form a rocky beach with a relatively flat platform known as a wave-cut terrace.

Some rocky shorelines are marked by relatively flat bedrock platforms known as benches, ranging from a few tens of feet (m) to thousands of feet (1 km) wide, typically followed inland by cliffs. These benches may be horizontal, gently seaward dipping, or inclined as many as 30 degrees toward the sea. Benches are formed by wave abrasion and quarrying of material away from cliffs, and develop along with cliff retreat from the shoreline. The waves must have enough energy to remove the material that falls from the cliffs, and the waves abrade the surface during high tides. Benches developed on flat-lying sedimentary rocks tend to be flat, whereas those developed on other types of rocks may be more rugged. An unusual type of chemical weathering may also play a role in the formation of wave-cut benches. The alternate wetting and drying leaves sea salts behind that promote weathering of the rock, making it easier for the waves to remove the material.

Along many coastlines, wave-cut benches or platforms may be found at several different levels high above sea level. These marine terraces generally form where tectonic forces are uplifting the coastline, such as along some convergent margins, and can be used to estimate the rates of uplift of the land if the ages of the various marine terraces can be determined.

A variety of other unusual erosional landforms are found along rocky shorelines, particularly where cliffs are retreating. Sea stacks are isolated columns of rock left by retreating cliffs, with the most famous being the Twelve Apostles, along the southern coast of Australia. Arches are sometimes preserved in areas of seastacks that have developed in horizontally layered sedimentary rocks, where waves erode tunnels through headlands.

REEF SYSTEMS

Reefs are wave-resistant, framework-supported carbonate or organic mounds generally built by carbonate-secreting organisms, or in some usages the term may be used for any shallow ridge of rock lying near the surface of the water. Reefs contain a plethora of organisms that together build a wave-resistant structure to just below the low-tide level in the ocean waters and provide shelter for fish and other organisms. The spaces between the framework are typically filled by skeletal debris, which together with the framework become cemented together to form a wave-resistant feature that shelters the shelf from high-energy waves. Reef organisms (presently consisting mainly of zooxanthellae) can survive only in the photic zone, so reef growth is restricted to the upper 328 feet (100 m) of the seawater.

Reefs are built by a wide variety of organisms, today including red algae, mollusks, sponges, and cnidarians (including corals). The colonial Scleractinia corals are presently the principal reef builders, producing a calcareous external skeleton characterized by radial partitions known as septa. Inside the skeleton are soft-bodied animals called polyps, containing symbiotic algae essential for the life cycle of the coral and the building of the reef structure. The polyps contain calcium bicarbonate that is broken down into calcium carbonate, carbon dioxide, and water. The calcium carbonate is secreted to the reef building its structure, whereas the algae photosynthesize the carbon dioxide, producing food for the polyps.

There are several different types of reefs, classified by their morphology and relationship to nearby landmasses. Fringing reefs grow along and fringe the coast of a landmass and are often discontinuous. They typically have a steep outer slope, an algal ridge crest, and a flat, sand-filled channel between the reef and the main shoreline. Barrier reefs form at greater distances from the shore than fringing reefs, and are generally broader and more continuous than fringing reefs. They are among the largest biological structures on the planet—for instance, the Great Barrier Reef of Australia is 1,430 miles (2,300 km) long. A deep, wide lagoon typically separates barrier reefs from the mainland. All of these reefs show a zonation from a high-energy side on the outside or windward side of the reef, grow fast, and have a smooth outer boundary. In contrast, the opposite side of the reef receives little wave energy and may be irregular and poorly developed, or grade into a lagoon. Many reefs also show a vertical zonation in the types of organisms present, from deepwater to shallow levels near the sea surface.

Atolls or atoll reefs form circular-, elliptical-, or semicircular-shaped islands made of coral that rise from deep water; atolls surround central lagoons, typically with no internal landmass. Some atolls do have small central islands, and these, as well as parts of the outer circular reef, are in some cases covered by forests. Most atolls range in diameter from half a mile to more than 80 miles (1–130 km), and are most common in the western and central Pacific Ocean basin and in the Indian Ocean. The outer margin of the semicircular reef on atolls is the most active site of coral growth, since it receives the most nutrients from upwelling waters on the margin of the atoll. On many atolls coral growth on the outer margin is so intense that the corals form an overhanging ledge from which many blocks of coral break off during storms, forming a huge pile of broken reef debris at the base of the atoll called talus slope. Volcanic rocks, some of which lie more than half a mile (1 km) below current sea level, underlay atolls. Since corals can grow only in very shallow water fewer than 65 feet (20 m) deep, the volcanic islands must have formed near sea level, grown coral, and subsided over time, with the corals growing at the rate that the volcanic islands were sinking.

Charles Darwin proposed such an origin for atolls in 1842 based on his expeditions on the HMS *Beagle* from 1831 to 1836. He suggested that volcanic islands were first formed with their peaks exposed above sea level. At this stage coral reefs were established as fringing reef complexes around the volcanic island. He suggested that with time the volcanic islands subsided and were eroded, but that the growth of the coral reefs was able to keep up with the subsidence. In this way, as the volcanic islands sank below sea level, the coral reefs continued to grow and eventually formed a ring circling the location of the former volcanic island. When Darwin proposed this theory in 1842, he did not know that ancient, eroded volcanic mountains underlay the atolls he studied. More than 100 years later, drilling confirmed his prediction that volcanic rocks would be found beneath the coralline rocks on several atolls.

With the advent of plate tectonics in the 1970s the cause of the subsidence of the volcanoes became apparent. When oceanic crust is created at midocean ridges, it is typically about 1.7 miles (2.7 km) below sea level. With time, as the oceanic crust moves away from the midocean ridges, it cools and contracts, sinking to about 2.5 miles (4 km) below sea level. In many places on the seafloor small volcanoes form on the oceanic crust a short time after the main part of the crust formed at the midocean ridge. These volcanoes may stick above sea level a few hundred meters. As the oceanic crust moves away from the midocean ridges, these volcanoes subside below sea level. If the volcanoes happen to be in the tropics where corals can grow, and if the rate of subsidence is slow enough for the growth of coral to keep up with subsidence, then atolls may form where the volcanic island used to be. If corals do not grow or cannot keep up with subsidence, then the island subsides below sea level and the top of the island gets scoured by wave erosion, forming a flat-topped mountain that continues to subside below sea level. These flat-topped mountains are known as guyots, many of which were mapped during exploration of the seafloor associated with military operations of World War II.

Reefs are extremely sensitive and diverse environments and cannot tolerate large changes in temperature, pollution, turbidity, or water depth. Reefs have also been subject to mining, destruction for navigation and even sites of testing nuclear bombs in the Pacific. Thus human-induced and natural changes in the shoreline environment pose a significant threat to the reef environment.

See also CORAL; DELTAS; ESTUARY; HURRICANES; OCEAN BASIN; SEA-LEVEL RISE.

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benthic, benthos The benthic environment includes the ocean floor and the benthos are those organisms that dwell on or near the seafloor. Bottom-dwelling benthos organisms include large plants that grow in shallow water, as well as animals that dwell on the seafloor at all depths.

Many of the sediments on the deep seafloor are derived from erosion of the continents and carried to the deep sea by turbidity currents, carried by wind (e.g., volcanic ash), or released from floating ice. Other sediments, known as deep-sea oozes, include pelagic sediments derived from marine organic activity. When small organisms such as diatoms die in the ocean, their shells sink to the bottom and over time can make significant accumulations. Calcareous ooze occurs at low to middle latitudes where warm water favors the growth of carbonate-secreting organisms. Calcareous oozes are not found in water more than 2.5–3 miles (4–5 km) deep because this water is under such high pressure that it contains a lot of dissolved CO_2, which dissolves carbonate shells. The depth below which all calcium-bearing shells and tests dissolve is known as the calcium carbonate compensation depth. Siliceous ooze is produced by organisms that use silicon to make their shell structure.

The benthic world is amazingly diverse, yet parts of the deep seafloor are less explored than the surface of the Moon. Organisms that live in the benthic community generally use one or more of three main strategies for living. Some attach themselves to anchored surfaces and get food by filtering it from the seawater. Other organisms move freely about on the ocean

Benthic organisms including crabs, anemones, clams, and mussels on ocean floor *(TheSupe87, 2008, Shutterstock, Inc.)*

bottom and get their food by predation. Still others burrow or bury themselves in the ocean bottom sediments and obtain nourishment by digesting and extracting nutrients from the benthic sediments. All the benthic organisms must compete for living space and food, with other factors including light levels, temperature, salinity, and the nature of the bottom controlling the distribution and diversity of some organisms. Species diversification is related to the stability of the benthic environment. Areas that experience large variations in temperature, salinity, and water agitation tend to have low species diversification, but may have large numbers of a few different types of organisms. In contrast, stable environments tend to show much greater diversity, with a larger number of species present.

There are a large number of different benthic environments. Rocky shore environments in the intertidal zone have a wide range of conditions from alternately wet and dry to always submerged, with wave agitation and predation being important factors. These rocky shore environments tend to show a distinct zonation in benthos, with some organisms inhabiting one narrow niche and other organisms in others. Barnacles and other organisms that can firmly attach themselves to the bottom do well in wave-agitated environments, whereas certain types of algae prefer areas from slightly above the low-tide line to about 33 feet (10 m) depth. The area around the low-tide mark tends to be inhabited by abundant organisms, including snails, starfish, crabs, mussels, sea anemones, urchins, and hydroids. Tide pools are highly variable environments that host specialized plants and animals including crustaceans, worms, starfish, snails, and seaweed. The subtidal environment may host lobster, worms, mollusks, and even octopus. Kelp, brown benthic algae, inhabit the subtidal zone in subtropical to subpolar waters and can grow down to a depth of about 130 feet (40 m), often forming thick underwater forests that may extend along a coast for many kilometers.

Sandy and muddy bottom benthic environments often form at the edges of deltas, sandy beaches, marshes, and estuaries. Many of the world's temperate to tropical coastlines have salt marshes in the intertidal zone and beds of sea grasses growing just below the low-tide line. Surface-dwelling organisms in these environments are known as epifauna, whereas organisms that bury themselves in the bottom sand and mud are called infauna. Many of these organisms obtain nourishment either by filtering seawater that they pump through their digestive system or by selecting edible particles from the seafloor. Deposit-feeding bivalves such as clams inhabit the area below the low-tide mark, whereas other deposit feeders may inhabit the intertidal zone. Other organisms that inhabit these environments include shrimp, snails, oysters, tube-building crustaceans, and hydroids.

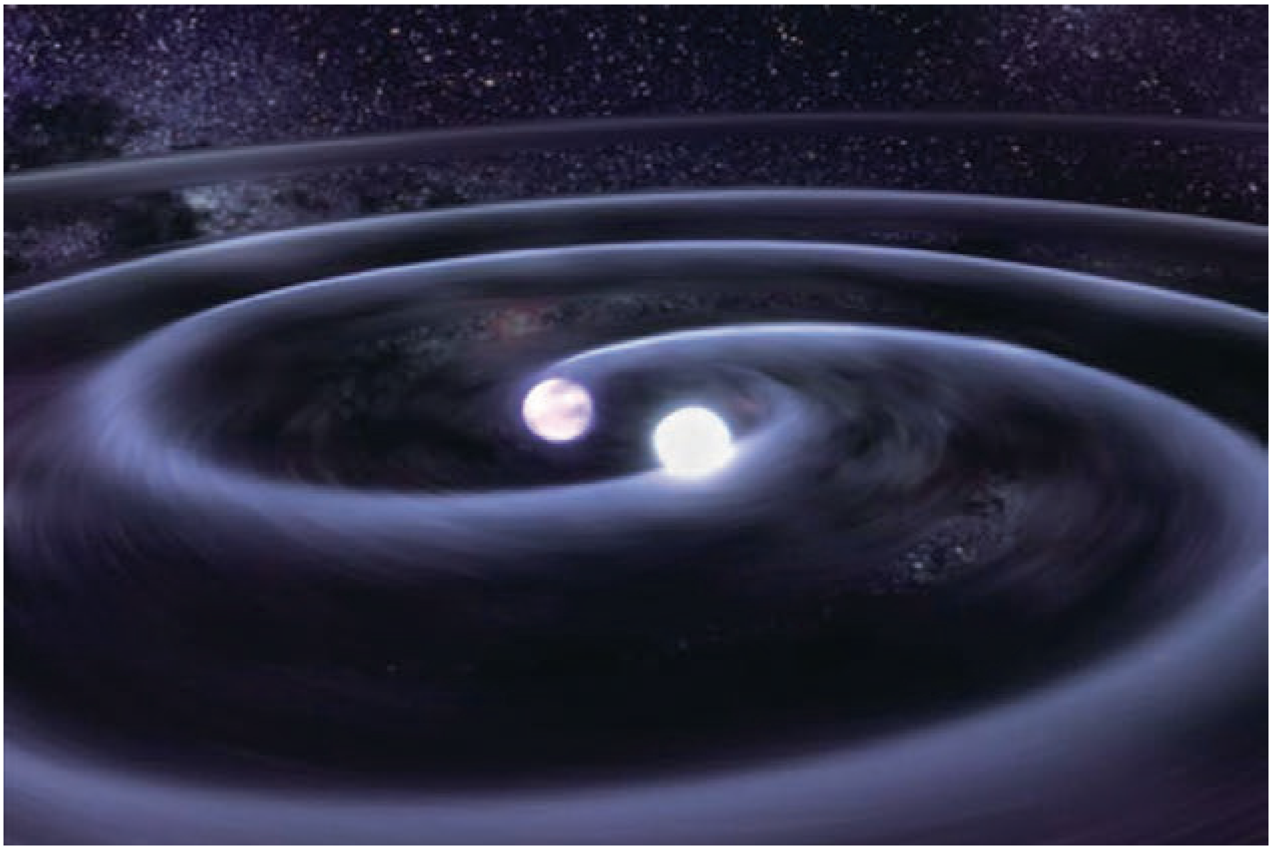
Coral reefs are special benthic environments that require warm water greater than 64.4°F (18°C) to survive. Colonial animals secrete calcareous skeletons, placing new active layers on top of the skeletons of dead organisms, and thus build the reef structure. Encrusting red algae, as well as green and red algae, produce the calcareous cement of the coral reefs. The reef hosts a huge variety and number of other organisms, some growing in symbiotic relationships with the reef builders, others seeking shelter or food among the complex reef. Upwelling waters and currents bring nutrients to the reef. The currents release more nutrients produced by the reef organisms. Some of the world's most spectacular coral reefs include the Great Barrier Reef, off the northeast coast of Australia, reefs along the Red Sea and Indonesia, and reefs in the Caribbean and south Florida.

Unique forms of life were recently discovered deep in the ocean near hot vents located along the midocean ridge system. The organisms that live in these benthic environments are unusual in that they get their energy from chemosynthesis of sulfides exhaled by hot hydrothermal vents, and not from photosynthesis and sunlight. The organisms that live around these vents include tube worms, sulfate-reducing chemosynthetic bacteria, crabs, giant clams, mussels, and fish. The tube worms grow to enormous size, some being 10 feet (3 m) long and 0.8–1.2 inches (2–3 cm) wide. Some of the bacteria that live near these vents include the most heat-tolerant (thermophyllic) organisms recognized on the planet, living at temperatures of up to 235°F (113°C). They are thought to be some of the most primitive organisms known, being both chemosynthetic and thermophilic, and may be related to some of the oldest life-forms that inhabited the Earth.

The deep seafloor away from the midocean ridges and hot vents is also inhabited by many of the main groups of animals that inhabit the shallower continental shelves. The number of organisms on the deep seafloor is few, however, and the animals tend to be much smaller than those at shallower levels. Some deepwater benthos similar to the hot-vent communities have recently been discovered living near cold vents above accretionary prisms at subduction zones, near hydrocarbon vents on continental shelves, and around decaying whale carcasses.

See also BEACHES AND SHORELINES; BLACK SMOKER CHIMNEYS; CONTINENTAL MARGIN.

binary star systems Most stars are parts of systems that include two or more stars that rotate in



NASA image captured by *Chandra X-Ray Observatory* of two white dwarf stars in binary star system J0806 *(UPI Photo/NASA/Landov)*

orbit around each other. When the system consists of two stars, it is known as a binary star system. Larger groups of stars are known as multiple star systems, or star clusters. Optical doubles are stars that appear to be binaries but are actually not related and just appear to be close in their visible configuration. In binary systems the two stars rotate about their common center of mass (the center of mass of both stars combined) and are held in place by the mutual gravitation attraction between them.

Binary star systems are classified according to how they appear to astronomers on Earth. Simple visual binaries are systems in which the two stars are far enough apart to be visibly distinct when viewed through a telescope from Earth, and each star is bright enough to be monitored separately from the other. In other cases the binary system may be too far, or the stars too close or small, to be visibly distinct from Earth, but the rotation of the stars around each other can be detected spectroscopically by observing shifts in the frequency and wavelength of a wave for an observer moving relative to the source of the waves, known as Doppler shifts, as each star alternately moves toward and away from the observer on Earth as the stars rotate around each other. The Doppler shift is recorded as a shift toward the blue end of the spectrum as the star moves toward the observer, and a redshift as the star moves away. Binary systems that can be detected only by using these spectroscopic Doppler shifts are known as spectroscopic binaries, and they are of two main types. Double-line spectroscopic binaries contain two distinct sets of spectral lines, one for each star, that shift back and forth from blue to redshifts as the star moves alternately toward and away from the observer. In these systems both stars are large and bright enough to be distinguished spectroscopically. In other systems one star may be too small or faint to be distinguished from the other, and the result is a single-line system in which one set of spectroscopic lines is observed to shift back and forth, caused by the stars rotating around each other even though they are too close to be resolved individually.

A rare class of binary star systems is known as eclipsing binaries. In these systems the orbital plane of the binary system is aligned nearly head-on with the line of sight from Earth, so as each star passes in front (in the line of sight) of the other, it blocks the light coming from the blocked star, and the amount of light observed from Earth alternately changes as each star passes periodically in front of the other. Observations of eclipsing binaries can yield information about each star's mass, orbits, orbital periods, radii, and luminosity or brightness.

The range in the orbital periods of binary star systems is very large, spanning from hours to centuries. Knowledge of the orbital periods, plus the distance to the binary system, can be used to determine additional physical properties of the binary system, such as the combined mass of the stars. If the distance of each star from the center of mass of the system can be measured, then the individual masses of each star can also be determined. Calculations based on observations of binary star systems have formed the basis for most of what is known about the masses of stars in the solar system.

See also ASTRONOMY; ASTROPHYSICS; EINSTEIN, ALBERT; ELECTROMAGNETIC SPECTRUM; UNIVERSE.

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biosphere The biosphere encompasses the part of the Earth that is inhabited by life, and includes parts of the lithosphere, hydrosphere, and atmosphere. Life evolved more than 3.8 billion years ago, and has played an important role in determining the planet's climate and insuring that it does not venture out of the narrow window of parameters that allow life to continue. In this way the biosphere functions as a self-regulating system that interacts with chemical, erosional, depositional, tectonic, atmospheric, and oceanic processes on the Earth.

Most of the Earth's biosphere depends on photosynthesis for its primary source of energy, driven ultimately by energy from the Sun. Plants and many bacteria use photosynthesis as their primary metabolic strategy, whereas other microorganisms and animals rely on photosynthetic organisms as food for their energy, and thus use solar energy indirectly. Most of the organisms that rely on solar energy live, by necessity, in the upper parts of the oceans (hydrosphere), lithosphere, and lower atmosphere. Bacteria are the dominant form of life on Earth (comprising about 5×10^{30} cells), and also live in the greatest range of environmental conditions. Some of the important environmental parameters for bacteria include temperature, between -41 to 235°F (-5 to 113°C), pH levels from 0 to 11, pressures between a near vacuum and 1,000 times atmospheric pressure, and supersaturated salt solutions to distilled water.

Bacteria and other life-forms exist with diminished abundance to several miles (kilometers) or more beneath the Earth's surface, deep in the oceans, and some bacterial cells and fungal spores are found in the upper atmosphere. The lack of nutrients and the lethal levels of solar radiation above the shielding effects of atmospheric ozone limit life in the upper atmosphere.

Soils and sediments in the lithosphere contain abundant microorganisms and invertebrates at shallow levels. Bacteria exist at much deeper levels and are being found in deeper and deeper environments as exploration continues. Bacteria are known to exist to about two miles (3.5 km) in pore spaces and cracks in rocks, and deeper in aquifers, oil reservoirs, and salt and mineral mines. Deep microorganisms do not rely on photosynthesis, but rather use other geochemical or geothermal energy to drive their metabolic activity.

The hydrosphere and especially the oceans teem with life, particularly in the near-surface photic zone environment where sunlight penetrates. At greater depths below the photic zone most life is still driven by energy from the Sun, as organisms rely primarily on food provided by dead organisms that filter down from above. In the benthic environment of the seafloor there may be as many as 10 billion (10^{10}) bacteria per milliliter of sediment. Bacteria also exist beneath the level that oxygen can penetrate, but the bacteria at these depths are anaerobic, primarily sulfate-reducing varieties. Bacteria are known to exist to greater than 2,789 feet (850 m) beneath the seafloor.

In 1977 a new environment for a remarkable group of organisms was discovered on East Pacific Rise and observed directly in 1979 by geologist Peter Lonsdale and his team from Woods Hole Oceanographic Institute in Massachusetts using the deep-sea submarine ALVIN. The organisms survive on the seafloor along the midocean ridge system, where hot hydrothermal vents spew heated nutrient-rich waters into the benthic realm. In these environments seawater circulates into the ocean crust where it is heated near oceanic magma chambers. This seawater reacts with the crust and leaches chemical components from the lithosphere, then rises along cracks or conduits to form hot black and white smoker chimneys that spew the nutrient-rich waters at temperatures of up to 662°F (350°C). Life has been detected in these vents at temperatures of up to 235°F (113°C). The vents are rich in methane, hydrogen sulfide, and dissolved reduced metals such as iron that provide a chemical energy source for primitive bacteria. Some of the bacteria around these vents are sulfate-reducing chemosynthetic thermophyllic organisms, living at high temperatures using only chemical energy and therefore exist independently of photosynthesis. These and other bacteria are locally so great in abundance that they provide the basic food source for other organisms, including spectacular worm communities, crabs, giant clams, and even fish.

See also ATMOSPHERE; BENTHIC, BENTHOS; BLACK SMOKER CHIMNEYS; SUPERCONTINENT CYCLES.

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black holes The final stage of stellar evolution for stars with a large mass may be a black hole, a superdense collection of matter that has collapsed from a giant star or stars, and has such a strong gravity field that nothing can escape from it, not even light. Black holes are known by physicists as a singularity, a point with zero radius and infinite density. These dense but invisible objects form when a star has at least three solar masses left in its core after it has completed burning its nuclear fuel. This stage of stellar evolution is typically marked by the star experiencing a supernova explosion, after which, if enough mass is left over, the star's nucleus collapses to a small point and warps space-time, forming a black hole. Black holes have such a strong gravitational field that they apparently draw material into them that is never to be seen again.

Black holes are one of the possible end states of old stars. Stars that have a low total mass (less than 1.4 solar masses) end their evolution as a white dwarf, whereas stars with masses between 1.4 and three solar masses may end their life cycle as a small dense mass known as a neutron star. When the mass of the dying star is greater than three solar masses, the star collapses as the nuclear fuel runs out. The gravitational attraction of the mass is so great that electrons and even neutrons cannot support the core against its own gravity, so it continues to collapse into what is called a singularity. There is no force known in nature that is strong enough to resist the gravitational attraction of a collapsing star once the pressure is so great that the neutrons degenerate and collapse. The force is so strong that not even light can escape from inside a black hole, hence the name.

The concept of a black hole as an infinitesimally small singularity with infinite mass is difficult to comprehend, in part because it is not adequately explained by the classical Newtonian laws of physics, or gravitational theory. To understand fully the workings of black holes it is necessary to move into the realm of quantum mechanics and Albert Einstein's theory of relativity. A quantitative treatment of relativity is beyond the scope of this book, but many aspects of Einstein's theories can be understood qualitatively. To understand how black holes work, it is necessary to know that nothing can travel faster than the speed of light, and that the gravitational force acts on everything, including electromagnetic radiation, or light.

To understand black holes, it is necessary to understand the concept of escape velocity. Objects on Earth must move 6.8 miles (11 km) per second to escape the pull of the Earth's gravitational attraction and move into open space. Escape velocity ν_e for any planetary or stellar object is proportional to the square root of the mass—of the body being escaped from divided by the square root of its radius *r,* which is the distance from the center of the body being escaped from and the location where the moving object is escaping. This can be written as

$$v_e\sqrt{\frac{2GM}{r}}$$

where G is the gravitational constant, $6.67428 \times 10^{-11}m^3kgs^{-1}$. This relationship means that for objects denser and smaller than the Earth but with the same mass, the escape velocity would need to be faster for any object to escape its gravitational field. As a massive object such as a huge star begins to collapse, therefore, the escape velocity required for anything to leave its gravitational field rises rapidly as the star shrinks from a large radius to a small object a fraction of its original size. If the star shrinks to a quarter of its original size, the escape velocity doubles—and as a star experiences a rapid collapse after a supernova, the escape velocity rises to such extremely high values that it is virtually impossible for any object to escape the star's gravitational pull. If an object the size of the Earth were to collapse to about 1/3 inch (1 cm), the escape velocity would be 186,000 miles per second (300,000 km/sec), the speed of light. From Einstein's theory of relativity, which states that even light is attracted by gravity, it becomes clear that at some point during the collapse of massive stars even light will no longer be able to escape the gravitational pull of the body, and the collapsed star will become dark forever. Since some large stars collapse to a size smaller than an elementary particle, the escape velocity becomes infinitely high, and the gravitational attraction becomes stronger and stronger. At this point the black hole can pull objects in, but nothing can ever escape. That is the meaning of the term *black hole.* The only way to detect a black hole is by its immense gravitational field, which can deflect light as it bends toward the huge gravitational pull. Astronomers use sophisticated measurements to tell when a star moves optically behind a black hole, and they can measure the deflection of the light. This allows for the determination of some of the physical properties (like mass, charge, and angular momentum) of the black hole.

Every object with a specific mass has a critical radius at which the escape velocity equals the speed of light. When the object is compressed to that radius, nothing can escape its gravitational pull—not even light—and the object becomes invisible. This critical radius is known as the Schwarzschild radius, named after the German physicist Karl Schwarzschild, who first described this phenomenon. The Sun has a Schwarzschild radius of about 9.8 feet (3 m), but stars with the mass of the Sun do not usually collapse to become black holes since they are too small. The smallest stellar objects that form black holes have about three solar masses, and the Schwarzschild radius for these stars is about 5.6 miles (9 km).

Another concept useful for understanding black holes is that of the event horizon, which is the surface of an imaginary sphere with a radius equal to the Schwarzschild radius, centered on a collapsing star. The event horizon is an imaginary surface, but can be thought of as the surface of the black hole, since beyond the event horizon, no event that happens can ever be heard, seen, or detected by any known means. The event horizon does not represent the size of the material that collapsed to form the black hole. Since this material should theoretically collapse to a tiny singularity, it merely represents the radius past which the gravitational pull of the dense black hole at the center of the sphere is so strong that nothing can escape once inside that radius.

Black holes are said to warp the space-time continuum in the way we understand it from a classical Newtonian mechanical way. According to Einstein's theory of relativity, all matter tends to warp space in its vicinity, and objects respond to this warp by changing their direction of movement as they approach other objects. Newtonian physics would describe this as a gravitational pull, whereas relativity theory suggests that the objects are just following the curved space that was distorted by the nearby massive object. The more massive the objects, the more they curve the space. In the case of black holes the warping of space is extreme because of the huge mass in the black hole, and at the event horizon, space is actually folded over upon itself, such that objects that cross the event horizon disappear from space forever.

As material falls into a black hole, the gravitational stresses are so great that they distort and tear apart objects as they plunge toward the event horizon. These objects become heated and emit radiation, so the regions surrounding black holes are sometimes emitters of strong radiation. Once the material crosses the event horizon, however, nothing can escape, not light, not radiation, and the mass is never seen or heard from again.

The gravity fields of black holes are so strong that it is virtually impossible to get close to one without being physically torn apart by the strong gravity, and the difference in the strength of the gravity from one end of any approaching object (or person) and the other end. Nonetheless it is interesting and informative to discuss what it might be like to approach, and even enter, a black hole. The first thing an outside observer of an object approaching a black hole would notice is that light, and other electromagnetic radiation coming from the object, shows a redshift (toward longer wavelengths) that increases as the object gets closer to the event horizon. This is not a Doppler shift caused by the motion of the object, as the object near the black hole would exhibit the redshift even if it were motionless with respect to the observer. This redshift is a quantum mechanical effect known as a gravitational redshift. Einstein's general theory of relativity shows that as photons (light) try to escape a strong gravitational field, they have to use up some of their energy. Photons are light, and they always move at the speed of light, so this loss of energy is equated with a decrease in frequency, or a lengthening of the wavelength of the light (or other electromagnetic radiation) coming from the object approaching the black hole. The distant observer measures this as a redshift. Interestingly, an observer on the object emitting the radiation would see no redshift, and the radiation (light) would have the same energy and wavelength as when it was emitted. These gravitational redshifts have been measured on light coming from many dense objects in the universe, and objects even the size of Earth and the Sun have detectable gravitational redshifts. The largest, by far, are from black holes.

Black holes distort the space-time continuum. Another strange quantum mechanical effect explained in Einstein's theory of general relativity is time dilation near massive objects such as black holes. A distant observer looking at a clock on the object approaching the black hole would notice that the clock (and time itself) moves progressively slower and slower as the object approaches the black hole's event horizon. When the object is at the event horizon, the clock (and time) would appear to stand still, and from the perspective of the outside observer, the object would be frozen at the event horizon forever, never entering past it. However, from the perspective of anyone on the object approaching the event horizon, there is no difference in the way time passes; each second seems like one second. The object and observer would simply pass through the event horizon and notice nothing different (assuming they could withstand the strong gravitational forces). Time dilation is difficult to understand but can be thought of in the same way that the redshift of electromagnetic radiation occurs. If time is considered to be measured, for instance, as the passage of a wavelength of light, each second corresponding to the passage of one wave crest, then as the wavelengths are increased by the gravitational redshift, the time is also gradually expanded until it appears to stop by the outside observer.

No one really knows what happens inside the event horizon of a black hole. The laws of physics do not adequately explain such dense small objects as singularities, and some new concepts are being investigated by physicists, such as a merging of the laws of quantum mechanics and general relativity into the field of quantum gravity—but these investigations are incomplete. There are many ideas, some approaching science fiction, that have been proposed for what may happen near the singularity at the center of the black hole's event horizon. Some models suggest that new states of matter are created; others have suggested that black holes may be gateways for matter and energy to enter other universes or to travel in time.

Black holes are difficult to detect, since they are invisible. Their huge gravitational field, however, and the energy released by matter outside the event horizon as it falls into the black hole may be detectable. There are several good candidates for possible black holes in the Milky Way Galaxy. The best may be a massive but invisible body in a binary star system known as Cygnus X-1. This possible black hole is orbiting with a supergiant star companion, and is known as a powerful X-ray source (presumably from the material approaching the event horizon). This binary star system has an orbital diameter of 12.4 million miles (20 million km) and an orbital period of 5.6 days, and the mass of the system is 30 times that of the Sun. Calculations show that the invisible component of this binary system has a mass of 5–10 times that of the Sun, enough to have formed a black hole. In this system it appears that hot gases are flowing from the supergiant star into the black hole companion, and this is the source of the X-ray radiation. Other calculations show that the invisible part of this binary star is small, less than 186,000 miles (300,000 km) across, and other calculations show that it is likely less than 186 miles (300 km) across. Thus Cygnus X-1 is one of the most likely candidates for a black hole in the Milky Way Galaxy. There are nearly a dozen other black hole candidates in the Milky Way Galaxy, and as the observational powers of physicists increase with new space-borne telescopes, more and more are being discovered. What is needed is a breakthrough in the field of quantum gravity to understand what may really happen underneath the event horizon.

See also ASTRONOMY; ASTROPHYSICS; BINARY STAR SYSTEMS; DWARFS (STARS); EINSTEIN, ALBERT; STELLAR EVOLUTION.

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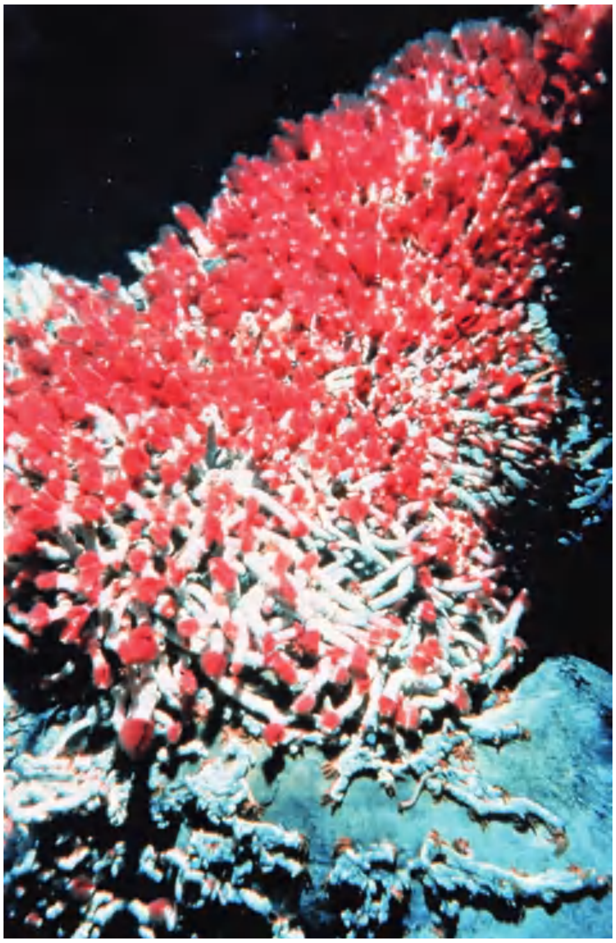
black smoker chimneys Black smoker chimneys are hydrothermal vent systems that typically form near active magmatic systems along the mid-ocean ridge system, approximately 2 miles (3 km) below sea level. They were first discovered by deep submersibles exploring the oceanic ridge system near the Galápagos Islands in 1979, and many other examples have been documented since then, including a number along the mid-Atlantic ridge.

Black smokers are hydrothermal vent systems that form by seawater percolating into fractures in the seafloor rocks near the active spreading ridge, where the water gets heated to several hundred degrees Celsius. This hot pressurized water leaches minerals from the oceanic crust and extracts other elements from the nearby magma. The superheated water and brines then rise above the magma chamber in a hydrothermal circulation system and escape at vents on the seafloor, forming the black smoker hydrothermal vents. The vent fluids are typically rich in hydrogen sulfides (H_2S), methane, and dissolved reduced metals, such as iron. The brines may escape at temperatures greater than 680°F (360°C), and when these hot brines come into contact with cold seawater, many of the metals and minerals in solution rise in plumes, since the hot fluids are more buoyant than the colder seawater. The plumes are typically about 0.6 miles (1 km) high and 25 miles (40 km) wide and can be detected by temperature and chemical anomalies, including the presence of primitive helium 3 isotopes derived from the mantle. These plumes may be rich in dissolved iron, manganese, copper, lead, zinc, cobalt, and cadmium, which



Black smoker chimney from the East Pacific Rise showing tube worms feeding at base of the chimney *(Science Source/Photo Researchers, Inc.)*

rain out of the plumes, concentrating these elements on the seafloor. Manganese remains suspended in the plumes for several weeks, whereas most of the other metals are precipitated as sulfides (e.g., pyrite, FeS_2; chalcopyrite, $CuFeS_2$; sphalerite, ZnS), oxides (e.g., hematite, Fe_2O_3), orthohydroxides (e.g., goethite, FeOOH), or hydroxides (e.g., limonite, $Fe(OH)_3$). A group of related hydrothermal vents that form slightly farther from central black smoker vents, known as white smokers, typically have vent temperatures between 500 and 572°F (260–300°C).

On the seafloor along active spreading ridges the hydrothermal vent systems form mounds that are typically 164–656 feet (50–200 m) in diameter, and some are more than 66 feet (20 m) high. Clusters of black smoker chimneys several meters high may occupy the central area of mounds and deposit iron-copper sulfides. White smoker chimneys typically form in a zone around the central mound, depositing iron-zinc sulfides and iron oxides. Some mounds on the seafloor have been drilled to determine their internal structure. The Trans-Atlantic Geotraverse (TAG) hydrothermal mound on the mid-Atlantic ridge is capped by central chimneys made of pyrite, chalcopyrite, and anhydrite, overlying massive pyrite breccia, with anhydrite-pyrite and silica-pyrite–rich zones found a few to tens of meters below the surface. Below this the host basalts are highly silicified, then at greater depths form a network of chloritized breccia. White smoker chimneys made of pyrite (FeS_2) and sphalerite (ZnS) rim the central mound. In addition to the sulfides, oxides, hydroxides, and orthohydroxides, including several percent copper and zinc, the TAG mound contains minor amounts of gold.

Seafloor hydrothermal mounds and particularly the black smoker chimneys host a spectacular community of unique life-forms, found only in these environments. Life-forms include primitive sulfate-reducing thermophilic bacteria, giant worms, giant clams, crabs, and fish, all living off the chemosynthetic metabolism made possible by the hydrothermal vent systems. Life at the black smokers draws energy from the internal energy of the Earth (not the Sun), via oxidation in a reducing environment. Some of the bacteria living at these vents are the most primitive organisms known on Earth, suggesting that early life may have resembled these chemosynthetic thermophilic organisms.

Black smoker chimneys and the entire hydrothermal mounds bear striking similarities to volcanogenic massive sulfide (VMS) deposits found in Paleozoic and older ophiolite and arc complexes including the Bay of Islands ophiolite in Newfoundland, the Troodos ophiolite in Cyprus, and the Semail ophiolite in Oman. Even older VMS deposits are common in Archean greenstone belts, and these are typically basalt or rhyolite-hosted chalcopyrite, pyrite, sphalerite, copper-zinc-gold deposits that many workers have suggested may be ancient seafloor hydrothermal vents. Interestingly, complete hydrothermal mounds with preserved black and white smoker chimneys have been reported recently from the 2.5 billion-year-old North China craton, in the same belt that the world's oldest well-preserved ophiolite is located.

The tectonic setting for the origin of life on the early Earth is quite controversial. Some favor environments in shallow pools, some favor deep ocean environments where the organisms could get energy from the chemicals coming out of seafloor hydrothermal vents. The discovery of black smoker types of hydrothermal vents in Archean ophiolite sequences is significant because the physical conditions at these midocean ridges more than 2.5 billion years ago would have permitted the inorganic synthesis of amino acids and other prebiotic organic molecules. Some scientists think that the locus of precipitation and synthesis for life might have been in small iron-sulfide globules, such as those that form around black smokers. Black smoker chimneys may provide a window into the past and the origin of life on Earth.

See also ASIAN GEOLOGY; BENTHIC, BENTHOS; BIOSPHERE; GREENSTONE BELTS; OPHIOLITES.

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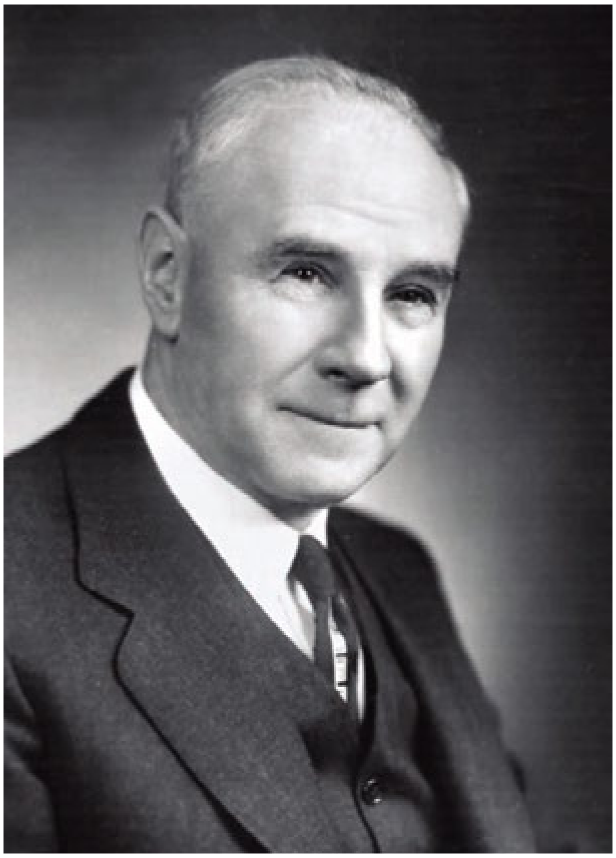
Bowen, Norman Levi (1887–1956) Canadian *Petrologist, Geologist* Dr. Norman Levi Bowen was one of the most brilliant igneous petrologists of the 20th century. Although he was born in Ontario, Canada, he spent most of his productive research career at the Geophysical Laboratories of the Carnegie Institute in Washington, D.C. Bowen studied the relationships between plagioclase feldspars and iron-magnesium silicates in crystallizing and melting experiments. From these experiments he derived the continuous and discontinuous reaction series explaining the sequence of crystallization and melting of these minerals in magmas. He also showed how magmatic differentiation by fractional crystallization can result from a granitic melt from an originally basaltic magma through the gradual crystallization of mafic minerals, leaving the felsic melt behind. Similarly he showed how partial melting of one rock type can result in a melt with a different composition than the original rock, typically forming a more felsic melt than the original rock and leaving a more mafic residue (or restite) behind. Bowen also worked on reactions between rocks at high temperatures and pressures, and the role of water in magmas. In 1928 Bowen published his pioneering book, *The Evolution of Igneous Rocks.*

N. L. Bowen is most famous for his works on the origin of igneous rocks, through the processes of magmatic differentiation by partial melting and magmatic differentiation by fractional crystallization. The phrase "magmatic differentiation by partial melting" refers to the process of forming magmas with differing compositions through the incomplete melting of rocks. For magmas formed in this way the composition of the magma depends on both the composition of the parent rock and the percentage of melt. If a rock melts completely, the magma has the same composition as the rock. However, rocks contain many different minerals, all of which melt at different temperatures. So if a rock is slowly heated, the resulting melt or magma will initially have the composition of the first mineral that melts, and then the first plus the second minerals that melt, and so on. If the rock melts completely, the magma will eventually end up with the same composition as the starting rock, but this does not always happen. Oftentimes the rock only partially melts, so that the minerals with low melting temperatures contribute to the magma, whereas the minerals with high melting temperatures did not melt and are left as a residue (or restite). In this way the end magma can have a different composition than the rock from which it was derived.

Just as rocks partially melt to form different liquid compositions, magmas may solidify to different minerals at different times to form different solids (rocks). This process also results in the continuous change in the composition of the magma—if one mineral is removed, the resulting composition is different. If some process removes these solidified crystals that have been removed from the system of melts, a new magma composition results.

The removal of crystals from the melt system may occur by several processes, including the squeezing of melt away from the crystals or by sinking of dense crystals to the bottom of a magma chamber. These processes lead to magmatic differentiation by fractional crystallization, as first described by Bowen, who systematically documented how crystallization



Norman Levi Bowen *(Queens University Archives)* of the first minerals changes the composition of the magma and leads to the formation of progressively more silicic rocks with decreasing temperature.

See also IGNEOUS ROCKS; PETROLOGY AND PETROGRAPHY.

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Brahe, Tycho (1546–1601) Danish *Nobleman, Astronomer* Tycho Brahe was born as Tyge Ottesen Brahe on December 14, 1546, in Scania, a region of Denmark now part of Sweden. He was born to nobility, the son of Otte Brahe and Beate Bille, at his family's ancestral home, Knutstorp Castle. His father was a nobleman in the court of the Danish king, and he had an older and a younger sister, and a twin brother who died soon after birth. Tycho's uncle, Danish nobleman Jorgen Brahe, took him from his parents when he was two years old, and from then he lived at his uncle's home at Tosterup Castle. Brahe was educated at a Latin school from age six until he was 12. He enrolled at the University of Copenhagen in 1559 at age 13 and studied law but gradually became more interested in astronomy. One of the defining moments in his career was at Copenhagen, when he witnessed an eclipse on August 21, 1560, at the precise time that was predicted by his professors and astronomers. Tycho purchased a book, called an ephemeris, that gives tables and positions of astronomical objects in the sky at different times. He studied this and many other texts for several years until he came to realize in 1563 that most astronomical texts of the time disagreed with one another. He wrote that astronomy could not progress by the types of haphazard observations that he was reading and suggested that long-term systematic study of the heavens was needed. With the naked eye and the help of his sister Sophia he made many measurements of the stars and planets and improved many astronomical instruments. Brahe's work preceded the invention of the telescope, however, and later observations by German astronomer Johannes Kepler using the telescope proved to be more accurate than Brahe's.

In 1565 Brahe's uncle Jorgen Brahe died after a night of heavy drinking with Frederick II, king of Denmark, when both men fell off a bridge into a river. Jorgen saved Frederick but caught pneumonia and later died. The next year Brahe and his friends were attending a dance at their professor's house and, after drinking considerably, he fought a duel with his fellow nobleman Manderup Parsbjerg in which Brahe lost part of his nose. This caused him to spend the rest of his life wearing prosthetic noses to hide his disfigurement. In 1571 Brahe's father died following a long illness, after which the son started building an astronomical observatory and alchemistry laboratory at Herrevad Abbey near Ljungbyhed, Scania (present-day southwest Sweden).

At the age of 26 Tycho Brahe fell in love with a commoner, Kirsten Jorgensdatter, and they moved to Copenhagen and were married three years later. They had eight children, six of whom lived to adulthood, and the couple stayed together until Brahe died in 1601 at the age of 54. Brahe became quite wealthy and hosted many parties in his castle, at which his tame pet elk and dwarf Jepp, who acted as court jester, were usually present. Brahe thought the dwarf was clairvoyant and had him spend meals under the table. At one of Brahe's parties the elk consumed too much beer and fell down a flight of stairs and died. On October 10, 1601, Brahe became ill at a banquet and died 11 days later. His death was a mystery for years, many having thought he died of bacteria from drinking too much at the banquet. Since manners at the time did not allow one to get up and leave during a meal, his bladder was thought to have stretched and caused infection. But exhumation of his remains has shown that he more likely died of mercury poisoning, either accidentally by swallowing mercury-tainted medicine, or possibly by being murdered. The book *Heavenly Intrigue: Johannes Kepler, Tycho Brahe, and the Murder Behind One of History's Greatest Scientific Discoveries* by Joshua Gilder and Anne-Lee Gilder (2005) speculates that Johannes Kepler is likely to have poisoned Brahe, having the means, motive, and opportunity.

SCIENTIFIC DISCOVERIES

Tycho Brahe grew up in a scientific era in which Aristotelian ideas that the universe was unchanging followed the principle of celestial immutability. While based at his observatory at Herrevad, Brahe made many observations on the planets and stars. On November 11, 1572, he made a discovery that changed the thinking about the universe. He observed a very bright star that appeared in the constellation Cassiopeia and showed that no star had been visible in that location before. At first other astronomers suggested that the bright object must be located below the orbit of the Moon, since Aristotle showed that the heavens were unchanging. Tycho

Brahe's systematic observations showed clearly that the object was far away and thus outside the Moon's orbit—it was a new object not previously observed. His continued observations over the next several months showed that the new star did not move relative to the planets. The world was convinced that the heavens now were changeable, and he published his observations in *De Stella Nova* in 1573, naming his new star a "nova." This nova, or new star, is now known to have been the supernova SN1572.

In addition to discovering the Cassiopeia supernova, Brahe became known as the best observational astronomer of the era before telescopes. He published in a star catalog many accurate observations on the positions of planets and stars. He proposed a model for the motion of the stars and planets in which the Sun orbited Earth, and the other planets orbited the Sun, a model that was a compromise between the Ptolemaic (named after the Greek astronomer Claudius Ptolemaeus, 83–168) view of the universe and Copernicus's heliocentric model, in which the planets orbited the Sun. This became known as the Tychonic System, even though it was originally proposed by the Greek philosopher Ponticus Heraclides in the fourth century B.C.E. The Tychonic system explained most of the observations of the motion of the planets, while still satisfying the powerful Catholic Church, which held that the Earth was the center of the universe. Brahe's observations were considered valid for some time after his death, as Kepler used Brahe's measurements of the motion of Mars to calculate the laws of planetary motion and to argue that the Copernican model with the Sun at the center of the universe was correct and that the other planets and Sun and stars were not orbiting Earth.

See also ASTRONOMY; SUPERNOVA.

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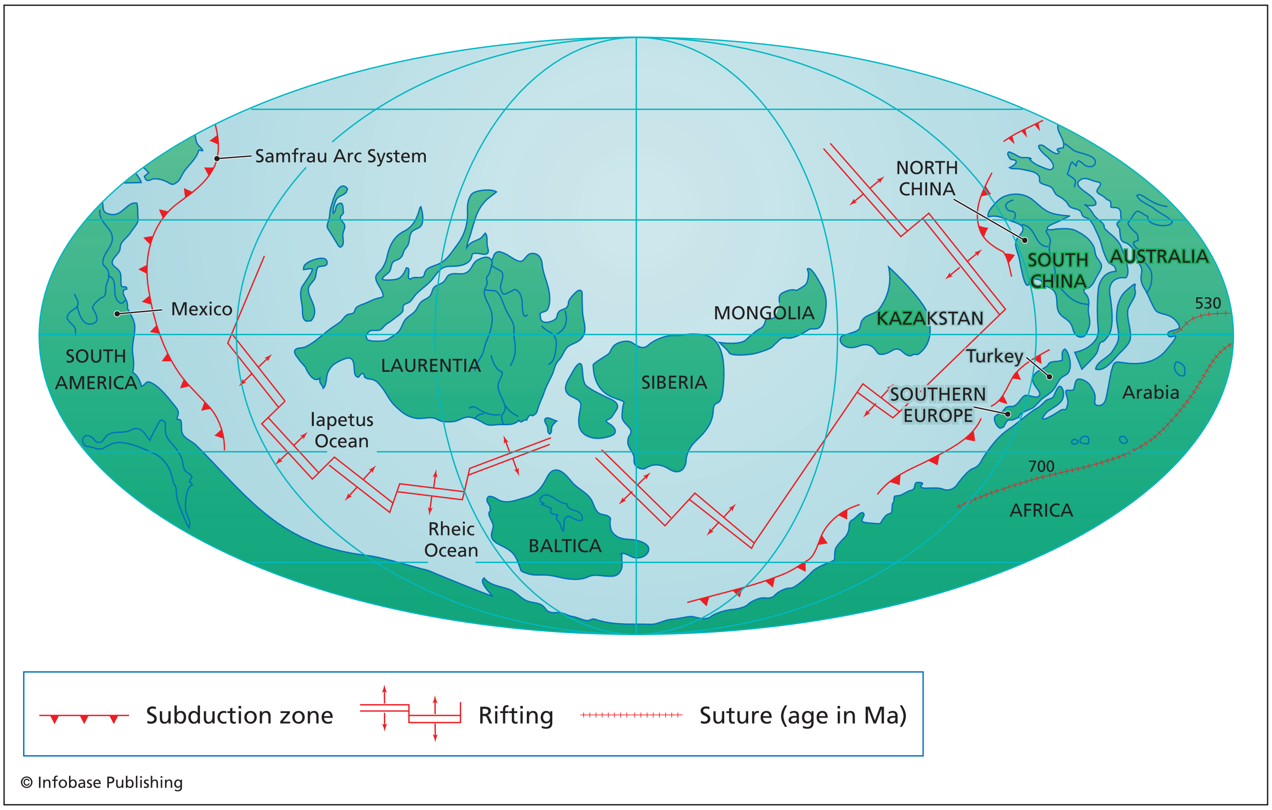
C

Cambrian The first geologic period of the Paleozoic Era and the Phanerozoic Eon, the Cambrian began 544 million years (Ma) ago and ended 505 million years ago. It is preceded by the Late Proterozoic Eon and succeeded by the Ordovician Period. The Cambrian System refers to the rocks deposited during this period. The Cambrian is named after Cambria, the Roman name for Wales, where the first detailed studies of rocks of this age were completed.

The Cambrian is sometimes called the age of invertebrates. Until this century scientists thought the Cambrian marked the first appearance of life on Earth. As the oldest period of the Paleozoic Era, meaning "ancient life," scientists now recognize the Cambrian as the short period in which a relatively simple pre-Paleozoic fauna suddenly diversified in one of the most remarkable events in the history of life. For the 4 billion years before the Cambrian explosion, life consisted mainly of single-celled organisms, with the exception of the remarkable Late Proterozoic soft-bodied Ediacaran (Vendian) fauna, sporting giant sea creatures that all went extinct by or in the Cambrian and have no counterpart on Earth today. The brief 40-million-year Cambrian saw the development of multicelled organisms, as well as species with exoskeletons, including trilobites, brachiopods, arthropods, echinoderms, and crinoids.

At the dawn of the Cambrian most of the world's continents were distributed within 60°N/S of the equator, and many of the continents that now form Asia, Africa, Australia, Antarctica, and South America were joined together in the supercontinent of Gondwana. These continental fragments had broken off an older supercontinent (Rodinia) between 700 and 600 million years ago, then joined together in the new configuration of Gondwana, with the final ocean closure of the Mozambique Ocean between East and West Gondwana occurring along the East African orogen at the Precambrian-Cambrian boundary. Even though the Gondwana supercontinent had formed only at the end of the Proterozoic, it was already breaking up and dispersing different continental fragments by the Cambrian.

Closure of the Mozambique Ocean in Neoproterozoic times sutured East and West Gondwana and intervening arc and continental terranes along the length of the East African orogen. Much active research in the earth sciences is aimed at providing a better understanding of this ancient mountain belt and its relationships to the evolution of crust, climate, and life at the end of the Precambrian and the opening of the Phanerozoic. There have been numerous rapid changes in our understanding of events related to the assembly of Gondwana. The East African orogen encompasses the Arabian-Nubian shield in the north and the Mozambique belt in the south. These and several other orogenic belts are commonly referred to as Pan-African belts, as many distinct belts in Africa and other continents experienced deformation, metamorphism, and magmatic activity in the general period 800–450 Ma. Pan-African tectonic activity in the Mozambique belt was broadly contemporaneous with magmatism, metamorphism, and deformation in the Arabian-Nubian shield. Geologists attribute the difference in lithology and metamorphic grade between the two belts to the difference in the level of exposure, with the Mozambican rocks interpreted as lower crustal equivalents of the rocks in the Arabian-Nubian shield.

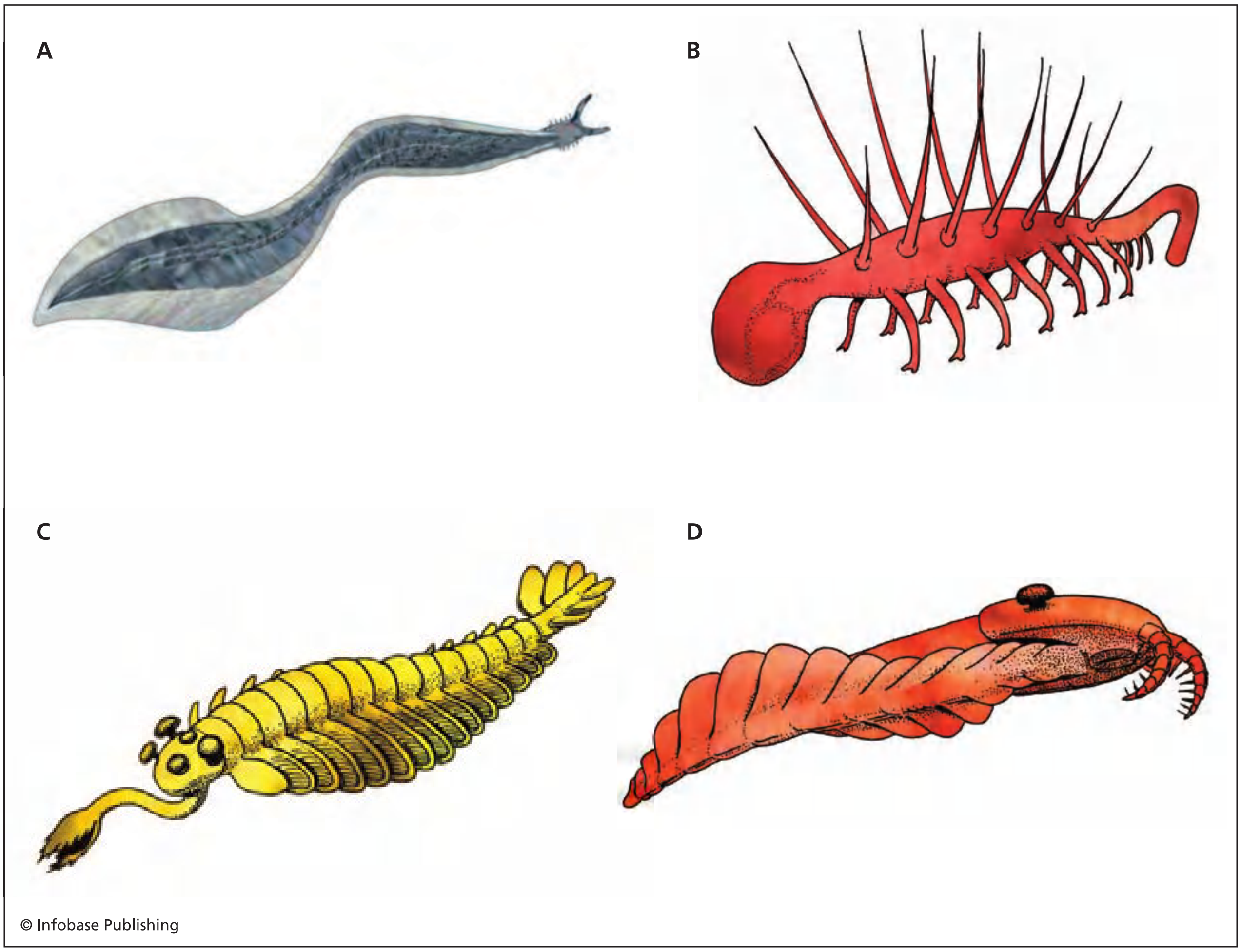


Paleogeographic plate reconstruction of the world during Late Precambrian times *(modeled after Kent Condie and Robert Sloan)*

The timing of Gondwana's amalgamation coincides remarkably with the Cambrian explosion of life, which has focused the research of many scientists on relating global-scale tectonics to biologic and climatic change. The dramatic biologic, climatic, and geologic events that mark Earth's transition into the Cambrian are likely linked to the distribution of continents and the breakup and reassembly of a supercontinent. The formation and dispersal of supercontinents causes dramatic changes in the Earth's climate, and changes the distribution of environmental settings for life to develop within. Plate tectonics and the formation and breakup of the supercontinents of Rodinia and Gondwana set the stage for life to diversify during the Cambrian explosion, bringing life from the primitive forms that dominated the Precambrian to the diverse fauna of the Paleozoic. The breaking apart of supercontinents creates abundant shallow and warm-water inland seas, as well as shallow passive margins along the edges of the rifted fragments. As rifting separated continental fragments from Rodinia, they moved across warm oceans, and new life-forms developed on these shallow passive margins and inland seas. When these "continental icebergs" carrying new life collided with the supercontinent Gondwana, the new life-forms could rapidly expand and diversify, then compete with the next organism brought in by the next continent. This process happened over and over again, with the formation and breakup of the two Late Proterozoic–Cambrian supercontinents of Rodinia and Gondwana.

North America began rifting away from Gondwana as it was forming, with the rifting becoming successful enough to generate rift-type volcanism by 570 million years ago and an ocean named Iapetus by 500 million years ago. The Iapetus Ocean saw some convergent activity in the Cambrian but experienced major contractional events during the Middle Ordovician. North and south China had begun rifting off of Gondwana in the Cambrian, as did Kazahkstan, Siberia, and Baltica (Scandinavia). The margins of these continental fragments subsided and accommodated the deposition of thick, carbonate passive-margin sequences that heralded the rapid development of life, and some of which are now petroleum provinces.

A Middle Cambrian sequence of fine-grained turbidites near Calgary, Alberta, Canada has yielded a remarkable group of extremely well-preserved fauna. In 1909 Charles D. Walcott discovered the



Sketches of some of the remarkable fauna from the Burgess shale, including (a) Pikaia, (b) Hallucigenia, (c) Opabinia, and (d) Anomocaris

Burgess shale, which preserved organisms deposited in a lagoon that was buried suddenly in anaerobic muds, which so well preserved the organisms that even the soft parts show fine detail. Fossils from the Burgess shale and related rocks have revealed much of what we know about the early life-forms in the Cambrian and represent the earliest-known fauna. The Burgess shale has yielded some of the best-preserved jellyfish, worms, sponges, brachiopods, trilobites, arthropods, mollusks, and first invertebrate chordates.

One of the important steps for the rapid expansion of life-forms in the Cambrian was the rapid radiation of acritarchs, small spores of planktonic algae such as green algae or dinoflagellates. The acritarchs were the primary source of food and the base of the food chain for the higher animals that later developed. Acritarchs appeared first during the Late Proterozoic, but 75 percent of all their taxa became extinct in the Late Proterozoic glaciation. The Late Proterozoic–Cambrian transition also saw the first appearance of trace fossils of soft-bodied organisms, showing that they developed and rapidly diversified in this period. Traces of worm paths are most common where they searched for food or burrowed into soft sediments.

Shelly fossils first appeared slightly later in the Cambrian, during the Tommotian, a 15-million-year stage added to the base of the Cambrian timescale in the 1970s. Most of the early shelly fossils were small (1–2 mm) conical shells, tubes, plates, or spicules made of calcite or calcium phosphate. They represent different phyla, including mollusks, brachiopods, armored worms, sponges, and archeocyathid reefs. The next major phase of the Cambrian radiation saw calcite shells added to trilobites, enabling their widespread preservation. Trilobites rapidly became abundant, forming about 95 percent of all preserved Cambrian fossils. But since trilobites form only 10 percent of the Burgess shale, this number could be biased in favor of the hard-shelled trilobites over other soft-bodied organisms. Trilobites experienced

Mid-Cambrian sea life reconstruction *(Tom McHugh/Photo Researchers, Inc.)*

five major extinctions in the Cambrian, each one followed by an adaptive radiation and expansion of new species into vacant ecological niches. Other arthropods that appeared in the Cambrian include crustaceans (lobsters, crabs, shrimp, ostracods, and barnacles) and chelicerates (scorpions, spiders, mites, ticks, and horseshoe crabs).

Mollusks also appeared for the first time at the beginning of the Cambrian, with the first clam (pelecypod) by the end of the Cambrian. Snails (gastropods) also emerged, including those with multiple gas-filled chambers. The cephalopods are other mollusks that had gas-filled chambers that appeared in the Cambrian. Echinoderms with hard skeletons first appeared in the Early Cambrian; these include starfish (asteroids), brittle stars (ophiuroids), sea urchins (echinoids), and sea cucumbers (holothuroids).

See also Gondwana, Gondwanaland; Paleozoic; Precambrian; supercontinent cycles.

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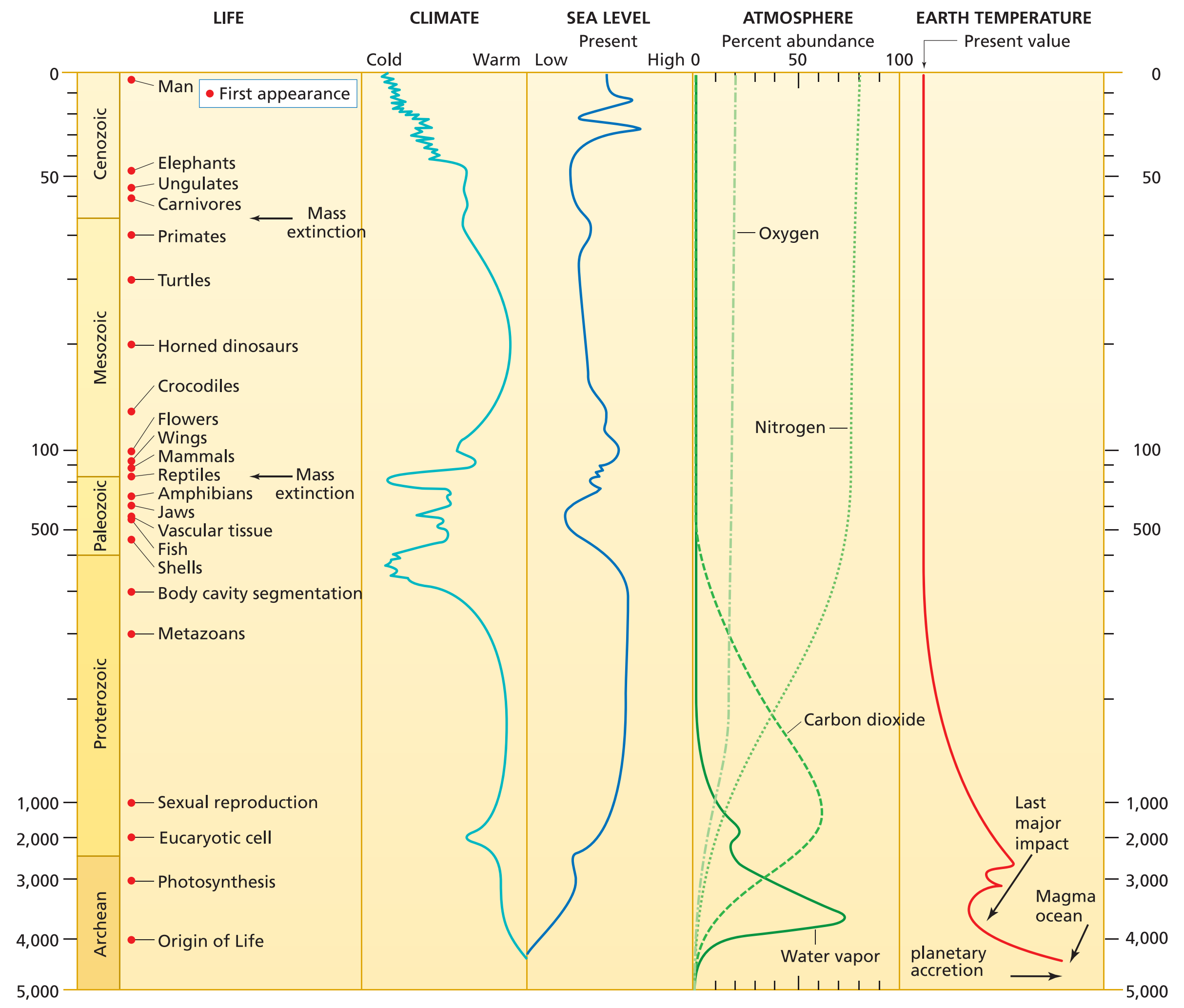
carbon cycle The carbon cycle is a complex series of processes in which the element carbon makes a continuous and complex exchange between the atmosphere, hydrosphere, lithosphere and solid Earth, and biosphere. Carbon is one of the fundamental building blocks of Earth, with most life-forms consisting of organic carbon, and inorganic carbon dominating the physical environment. The carbon cycle is driven by energy flux from the Sun and plays a major role in regulating the planet's climate.



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Graphs showing changes of CO_2, O_2, and temperature in the atmosphere with time *(modeled after Kent Condie and Robert Sloan)*

Several main processes control the flux of carbon on the Earth, and these processes are presently approximately balanced. Assimilation and dissimilation of carbon, by photosynthesis and respiration by life, cycles about 10^{11} metric tons of carbon each year. Some carbon is simply exchanged between systems as carbon dioxide (CO_2), and other carbon undergoes dissolution or precipitation as carbonate compounds in sedimentary rocks.

Atmospheric carbon forms the long-lived compounds carbon dioxide and methane, and the compound carbon monoxide, which has a short atmospheric residence time. Global temperatures and the amount of carbon (chiefly as CO_2) in the atmosphere are closely correlated, with more CO_2 in the atmosphere causing higher temperatures. Whether increased carbon flux in the atmosphere from the carbon cycle forces global warming or whether global warming causes an increase in the carbon flux remains undetermined. Since the industrial revolution, humans have increased CO_2 emissions in the atmosphere, and this has also caused measurable global warming, showing that increased carbon flux can control global temperatures.

The oceans are the largest carbon reservoir on the planet, containing more than 60 times as much carbon as the atmosphere. Dissolved inorganic carbon forms the largest component, followed by the more mobile dissolved organic carbon. The oceans are stratified into three main layers. The well-mixed surface layer is about 246 feet (75 m) thick and overlies the thermocline, a stagnant zone characterized by decreasing temperature and increasing density to its base at about 0.6-mile (1-km) depth. Below this lie the deep cold-bottom waters where dissolved CO_2 transferred by descending cold saline waters in polar regions may remain trapped for thousands of years. Cold polar waters contain more CO_2 because gases are more soluble in colder water. Some, perhaps large amounts, of this carbon becomes incorporated in gas hydrates, which are solid, icelike substances made of cases of ice molecules enclosing gas molecules like methane, ethane, butane, propane, carbon dioxide, and hydrogen sulfide. Gas hydrates have recently been recognized as a huge global energy resource, with reserves estimated to be at least twice that of known fossil fuel deposits. However, gas hydrates form at high pressures and cold temperatures, and extracting them from the deep ocean without releasing huge amounts of CO_2 into the atmosphere may be difficult.

Carbon is transferred to the deep ocean by its solubility in seawater, whereas organic activity (photosynthesis) in the oceanic surface layer accounts for 30–40 percent of the global vegetation flux of carbon. About 10 percent of the carbon used in respiration in the upper oceanic layer is precipitated out and sinks to the lower oceanic reservoir.

The majority of Earth's carbon is locked up in sedimentary rocks, primarily limestone and dolostone. This stored carbon reacts with the other reservoirs at a greatly reduced rate (millions and even billions of years) compared with the other mechanisms discussed here. Some cycles of this carbon reservoir are related to the supercontinent cycle and the weathering of carbonate platforms when they are exposed by continental collisions.

Earth's living biomass, the decaying remains of this biomass (litter), and soil all contain significant carbon reserves that interact in the global carbon cycle. Huge amounts of carbon are locked in forests, as well as in arctic tundra. Living vegetation contains about the same amount of carbon as is in the atmosphere, whereas the litter or dead biomass contains about twice the amount in the living biomass. Plants absorb an estimated 100 gigatons of carbon a year and return about half of this to the atmosphere by respiration. The remainder is transformed to organic carbon and incorporated into plant tissue and soil organic carbon.

Understanding the global carbon cycle is of great importance for predicting and mitigating climate change. Climatologists, geologists, and biologists are just beginning to understand and model the consequences of changes to parts of the system induced by changes in other parts of the system. For instance, a current debate centers on how plants respond to greater atmospheric CO_2. Some models indicate that they may grow faster under enhanced CO_2, tending to pull more carbon out of the atmosphere in a planetary self-regulating effect known as the fertilization effect. Many observations and computer models are being performed to investigate the effects of natural and human-induced changes (anthropogenic) in the global carbon cycle, and to understand better what the future may hold for global climates.

See also GEOCHEMICAL CYCLES; GLOBAL WARMING; HYDROCARBONS AND FOSSIL FUELS.

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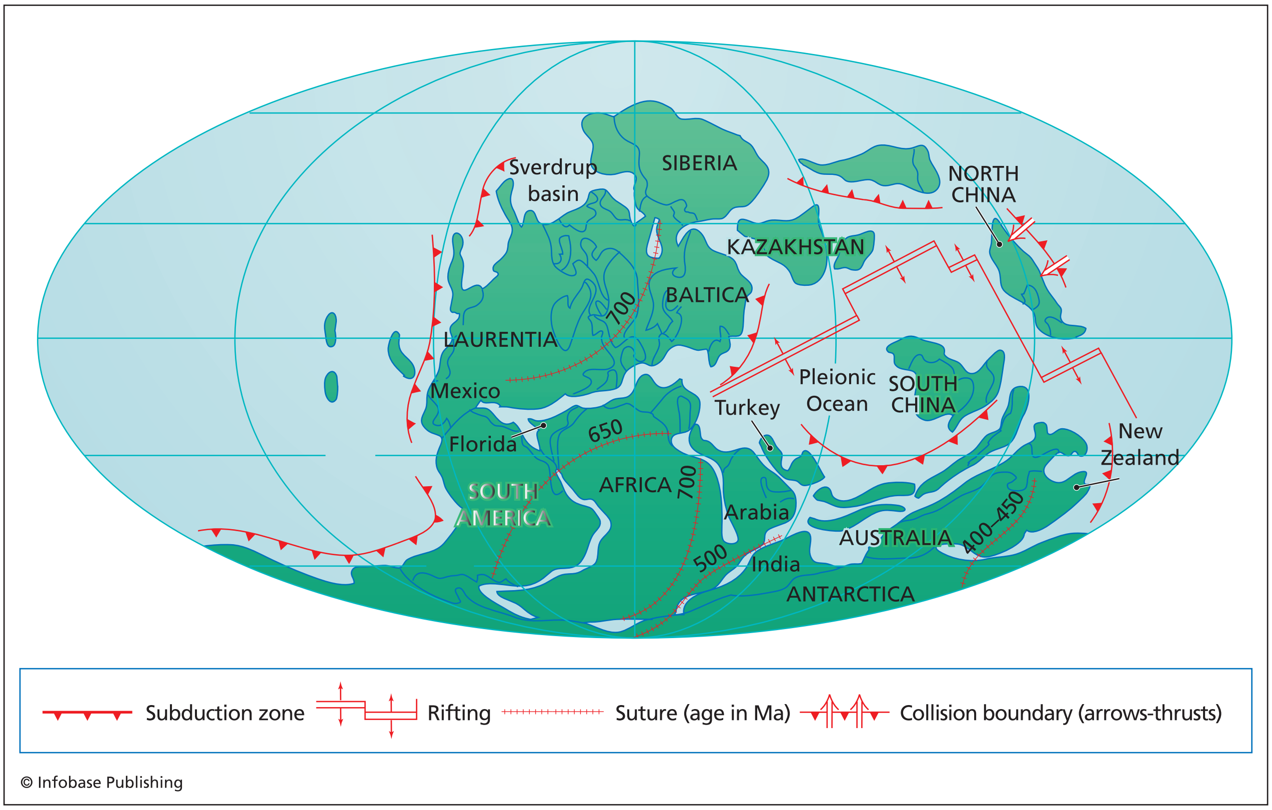
Carboniferous

The Carboniferous is a Late Paleozoic geologic period in which the Carboniferous System of rocks was deposited between 355 and 285 million years (Ma) ago. The system was named after coal-bearing strata in Wales and has the distinction of being the first formally established stratigraphic system. In the United States it is customary to use the divisions Mississippian Period (355–320 Ma) and Pennsylvania Period (320–285 Ma), whereas Europeans and the rest of the world refer to the entire interval of time as the Carboniferous Period and divide the rocks deposited in the period into two subsystems, the Upper and Lower, and five series.

The Carboniferous is known as the age of amphibians and the age of coal. The supercontinent Pangaea straddled the equator in the early Carboniferous, with warm climates dominating the southern (Gondwana) and northern (Laurasia) landmasses. In the Lower Carboniferous giant seed ferns and great coal forests spread across much of Gondwana and Laurasia, and most marine fauna that developed in the Lower Paleozoic flourished. Brachiopods, however, declined in number and species. Fusulinid foraminifera appeared for the first time. Primitive amphibians roamed the Lower Carboniferous swamps, along with swarms of insects including giant dragonflies and cockroaches.

In the Early Carboniferous (Mississippian), Gondwana was rotating northward toward the northern Laurentian continent, closing the Rheic Ocean. Continental fragments that now make up much of Asia were rifting from Gondwana, and the west coasts of North and South America were subduction-type convergent margins open to the Panthallassic Ocean. Several arc and other collisions with North America were underway, including the Antler Orogeny in the



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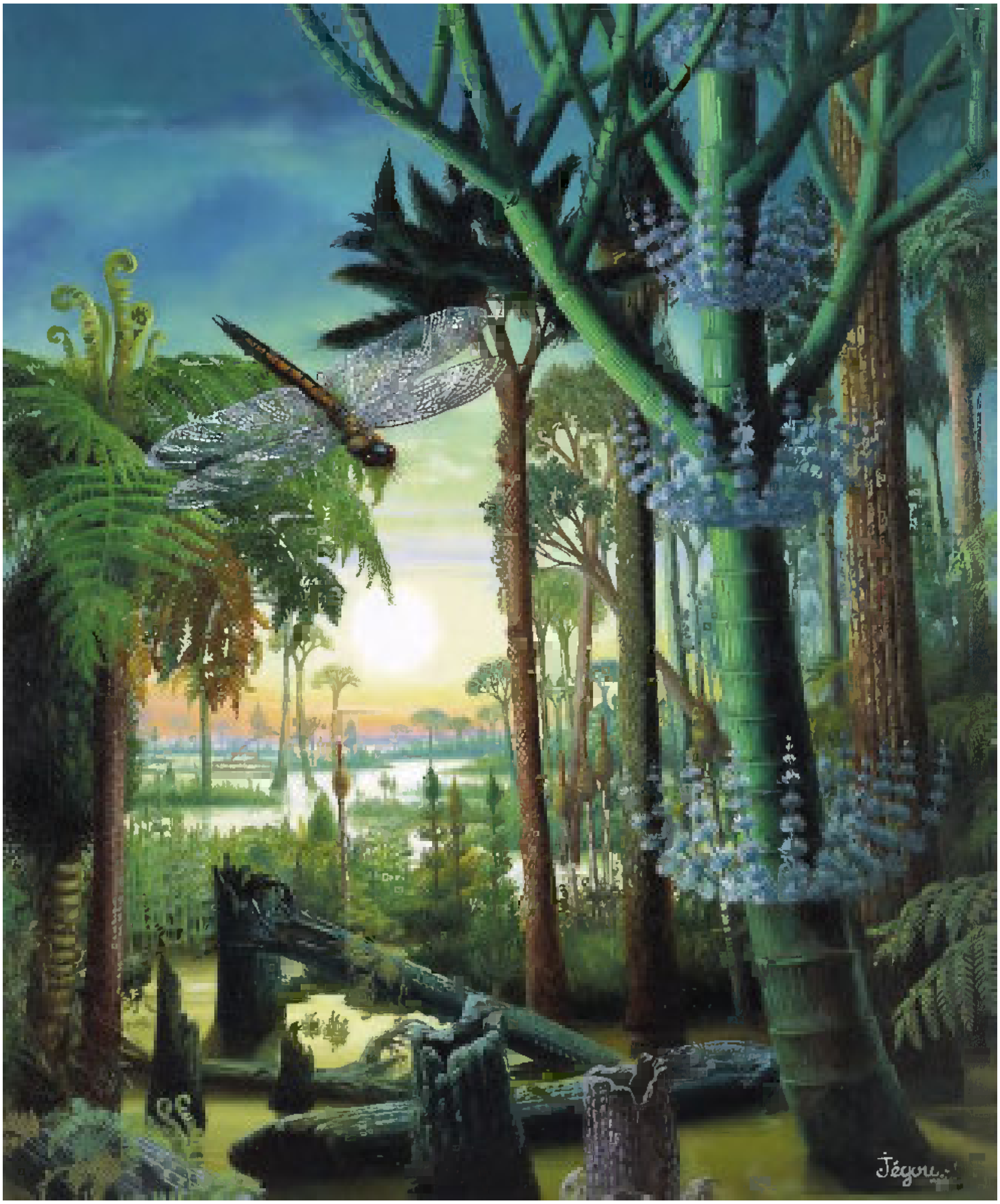
Paleogeographic map of Gondwana in the Carboniferous *(modeled after Kent Condie and Robert Sloan)*

western United States. The Hercynian Orogeny in Europe marked the collision between Baltica, southern Europe, and Africa. In the Late Carboniferous (Pennsylvanian), Laurentia and Gondwana finally collided, forming the single large landmass of Pangaea. This collision produced the Alleghenian Orogeny in the Appalachians of the eastern United States and the Ouachita Orogeny in the southern United States and South America, and formed the ancestral Rocky Mountains. In Asia Kazakhstan collided with Siberia, forming the Altai Mountains. Several microcontinents were rifted off the Gondwana continents to be accreted to form much of present-day Asia.

Global climates in the Carboniferous ranged from tropical around much of Laurentia and northern Gondwana, to polar on southern Gondwana, which experienced glaciation in the Pennsylvanian. This widespread glaciation formed in response to Gondwana migrating across the South Pole and is characterized by several advances and retreats and glacial deposits on Africa, Australia, South America, and India. Coal formed at both high and low latitudes in the Pennsylvanian, reflecting the warm climates from easterly trade winds around the closing Rheic Ocean and future opening of the Tethys Ocean. Most of the coal deposits formed in foreland basins associated with continental collisions.

Many sedimentary deposits of the Carboniferous age worldwide show development in a repetitive cycle, including accumulation of organic material (vegetation), deposition of carbonates, deposition of clastic sands, and erosion to sea level and soil development. These types of sedimentary deposits have become known as cyclothems; they reflect a uniform fluctuation of sea level by 500–650 feet (150–200 m). Analysis of the ages of each cyclothem has led to the recognition that each cycle represents 300,000 years, but the cause of the repetitive cycles remains a mystery. They may be related to cyclical variations in orbital parameters (Milankovitch cycles) or to variations in the intensity of the southern glaciation.

Extinctions in the Late Devonian paved the way for rapid expansion of new marine invertebrate forms in many ecological niches. Radiations in the brachiopods, ammonoids, bryozoans, crinoids, foraminifera, gastropods, pelcypods, and calcareous algae became widespread. Crinoids were particularly abundant in the Mississippian, forming dense submarine gardens, along with reefs made of bryozoans and calcareous algae. Fusulinid foraminifera with distinctive coiled forms evolved at the beginning of the Pennsylvanian and serve as a useful index fossil since they evolved so quickly and are abundant in many environments.



Artwork of Carboniferous landscape, including scale trees, ferns, seed ferns, and giant dragonflies *(Publiphoto/ Photo Researchers, Inc.)*

Land plants originated in the Devonian and saw additional diversification in the Carboniferous. Chordates, a prominent gymnosperm with long, thin leaves, flourished in the Mississippian, whereas conifers appeared in the Late Pennsylvanian. The tropical coal forests of the Pennsylvanian had trees that were more than 100 feet (30 m) tall, including the prominent Lepidodendron and Calamites trees and the seed-bearing Glossopteris shrub, which covered much of the cooler parts of Gondwana. Warm climates in the low-latitude coal swamps led to a flourishing fungi flora. The dense vegetation of the Carboniferous led to high levels of atmospheric oxygen, estimated to have made up about 35 percent of the gases in the atmosphere, compared with present-day levels of 21 percent.

The insects radiated in the Early Pennsylvanian and included the wingless hexapods and the primitive Paleoptera, ancestors of the modern dragonfly and mayfly. A giant Pennsylvanian dragonfly had a wingspan of 24 inches (60 cm) and preyed largely on other insects. Exopterygota, primitive crickets and cockroaches, appeared in the Pennsylvanian. Endopterygota, the folding-wing insects including flies and beetles, did not appear until the Permian.

The Carboniferous is famous for the radiation of amphibians. By the end of the Mississippian 10 different amphibian families had appeared, living mostly in water and feeding on fish. Eryops and other amphibians of this time resembled crocodiles, and include relatives of modern frogs and salamanders. Embolomeres evolved into large (up to 13 feet, or 4 m) eel-like forms with small legs, some living on land and eating insects. Leopospondyls remained in the water, eating mollusks and insects. The earliest known reptile, westlothiana, evolved from the amphibians in the Late Mississippian by 338 Ma ago. The transition from amphibians to reptiles occurred quickly, within a few tens of millions of years after the origin of amphibians. Amniotes are four-legged animals (tetrapods) that produced eggs similar to the modern bird egg, and include reptiles with scales. The rise of amniotes is a major evolutionary step, since the older amphibians underwent an early tadpole stage in which the young are vulnerable to prey. In contrast, the eggs of the amniotes and later reptiles provided enough food for the growth of the embryo in a safer environment and lessened the dependence on water, allowing them to move further inland. Descendants of the amniotes include mammals and birds.

The evolutionary transition between reptiles and mammals is gradual, with more intermediate evolutionary steps known than for any other high-order taxa. Like many other major evolutionary periods in Earth history, this evolutionary step occurred during a supercontinental amalgamation, enabling many species to compete. Many species intermediate between reptiles and mammals (the so-called mammal-like reptiles), and these dominated the land fauna for about 100 million years until the period of the dinosaurs began in the Permian. Mammal-like reptiles include two orders: Pelycosaurs and Therasids. The mammal-like reptiles had evolved into true mammals by this time but did not become dominant until the dinosaurs were killed off at the end of the Cretaceous.

See also GONDWANA, GONDWANALAND; MILANKOVITCH CYCLES; PALEOCLIMATOLOGY; PALEOZOIC; PANGAEA.

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cave systems, caves Caves are underground openings or passageways in rock that are larger than individual spaces between the constituent grains of the rock. The term *cave* is often reserved for spaces that are large enough for people to enter. Some scientists use the term to describe any rock shelter, including overhanging cliffs. Many caves are small pockets along enlarged or widened cavities, whereas others are huge open underground spaces. The largest cave in the world is the Sarawak Chamber in Borneo, with a volume of 65 million cubic feet (20 million cubic meters). The Majlis Al Jinn (Khoshilat Maqandeli) Cave in Oman is the second-largest known cave; it is big enough to hold several of the sultan of Oman's royal palaces, with a 747 flying overhead. Its main chamber exceeds 13 million cubic feet (4 million cubic meters), larger than the biggest pyramid at Giza. Other large caves include the world's third-, fourth-, and fifth-largest caves, the Belize Chamber, Salle de la Verna, and the largest "Big Room" of Carlsbad Cavern, a chamber 4,000 feet long (1,200 m), 625 feet wide (190 m), and 325 feet high (100 m). Each of these has a volume of at least 3 million cubic feet (1 million cubic meters). Some caves form networks of linked passages that extend for many miles. Mammoth Cave in Kentucky, for instance, has at least 300 miles (485 km) of interconnected passageways. While the caves are forming, water flows through these passageways in underground stream networks.

The formation of caves and sinkholes in karst regions begins with a process of dissolution. Rainwater that filters through soil and rock may work its way into natural fractures or breaks in the rock, and chemical reactions that remove ions from the limestone slowly dissolve and carry away in solution parts of the limestone. Fractures are gradually enlarged, and new passageways are created by groundwater flowing in underground stream networks through the rock. Dissolution of rocks is the most effective if the rocks are limestone and the water is slightly acidic (acid rain greatly helps cave formation). Carbonic

Limestone cave stalagmites and stalactites in Israel *(Joshua Haviv, Shutterstock, Inc.)*

acid (H_2CO_3) in rainwater reacts rapidly with the limestone (at typical rates of a few millimeters per thousand years), creating open spaces, cave and tunnel systems, and interconnected underground stream networks.

Many caves are decorated with natural deposits of minerals that coat the cave walls, hang from the cave ceiling, or protrude upward from the floor. Speleothems are any secondary mineral deposit formed in a cave by the action of groundwater. Most speleothems are made of carbonate minerals such as calcite, aragonite, or dolomite, but some are made of silicates and evaporites. Dripstone and flowstone are the most common carbonate speleothems. Yellow, brown, orange, tan, green, and red colors in dripstone and flowstone are formed through staining by organic compounds, oxides derived from overlying clays and soils, and rarely by ionic substitution in the carbonate minerals. Dripstone forms where water enters the cave through joints, bedding planes, or other structures and degasses carbon dioxide (CO_2) from water droplets, forming a small ring of calcite before each drop breaks free and falls into the cave. Each succeeding drop deposits another small ring of calcite, eventually forming a hollow tube called a straw stalactite. Additional growth can occur on the outside of the straw stalactite, forming a wedge-shaped, hanging calcite deposit. Drops that fall to the cave floor below deposit additional calcite, forming a mound-shaped stalagmite. These have no central canal but consist of a series of layers deposited over each other and typically are symmetric about a vertical axis. Flowstone is a massive secondary carbonate deposit formed by water that moves as sheet flows over cave walls and floors. The water deposits layered and terraced carbonate with complex and bizarre shapes, with shapes and patterns determined by the flow rates of the water and the shape of the cave walls, shelves, and floor. Draperies are layered deposits with furled forms intermediate between dripstone and flowstone.

Less common types of speleothems include shields, massive platelike forms that protrude from cave walls. They are fed by water that flows through a medial crack separating two similar sides of the shield, with the crack typically parallel to regional joints in the cave.

Some speleothems have erratic forms not controlled by joints, walls, or other structures. Helictites are curved stalactitelike forms with a central canal; anthodites are clusters of radiating crystals such as aragonite and a variety of botryoidal forms that resemble beads or corals. Moonmilk is a wet powder or wet pasty mass of calcite, aragonite, or magnesium carbonate minerals. Travertine forms speleothems in cave systems in which the waters are saturated in carbon dioxide.

Evaporite minerals form deposits in some dry, dusty caves where the relative humidity drops to below 90 percent and the waters have dissolved anions. Gypsum is the most common evaporite mineral found as a speleothem, with magnesium, sodium, and strontium sulfates being less common. Phosphates, nitrates, iron minerals, and even ice form speleothems in other less common settings.

See also KARST.

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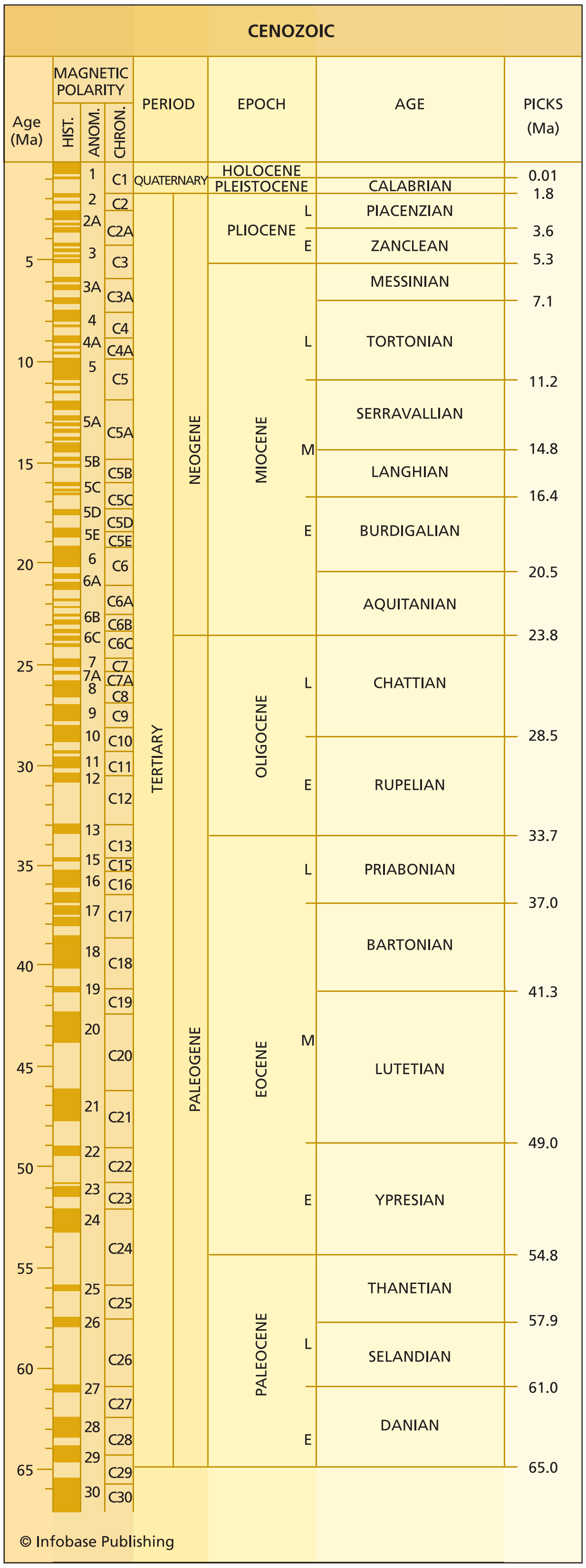
Cenozoic The Cenozoic Era marks the emergence of the modern Earth, starting at 66 million years ago and continuing until the present. Also spelled Cainozoic and Kainozoic, the term *Cenozoic* is taken from the Greek meaning recent life and is commonly referred to as the age of the mammals. Cenozoic divisions include the Tertiary (Paleogene and Neogene) and Quaternary Periods, and the Paleocene, Eocene, Oligocene, Miocene, Pliocene, Pleistocene, and Holocene Epochs.

Modern ecosystems developed in the Cenozoic, with the appearance of mammals, advanced mollusks, birds, modern snakes, frogs, and angiosperms, such as grasses and flowering weeds. Mammals developed rapidly and expanded to inhabit many different environments. Unlike the terrestrial fauna and flora, the marine biota underwent only minor changes, with the exception of the origin and diversification of whales.

CRETACEOUS-TERTIARY BOUNDARY

The Cenozoic began after a major extinction at the Cretaceous-Tertiary boundary, marking the boundary between the Mesozoic and Cenozoic Eras. This extinction event was probably caused by a large asteroid impact that hit Mexico's Yucatán Peninsula near Chicxulub at 66 million years ago. Dinosaurs, ammonites, many marine reptile species, and a large number of marine invertebrates suddenly died off, and the planet lost about 26 percent of all biological families and numerous species. Some organisms were dying off slowly before the dramatic events at



Cenozoic timescale

the close of the Cretaceous, but a clear, sharp event occurred at the end of this time of environmental stress and gradual extinction. Iridium anomalies have been found along most of the clay layers that mark this boundary, considered by many to be the "smoking gun," indicating an impact origin for the cause of the extinctions. An estimated one-half million tons of iridium are present in the Cretaceous-Tertiary boundary clay, equivalent to the amount that would be contained in a meteorite with a 6-mile (9.5-km) diameter. Some scientists have argued that volcanic processes within the Earth can produce iridium, and an impact is not necessary to explain the iridium anomaly. But, the presence of other rare elements and geochemical anomalies along the Cretaceous-Tertiary boundary supports the idea that a huge meteorite hit the Earth at this time.

Many features found around and associated with an impact crater on the Yucatán Peninsula suggest that this site is the crater associated with the death of the dinosaurs. The Chicxulub crater is about 66 million years old and lies half-buried beneath the waters of the Gulf of Mexico and half on land. Tsunami deposits of the same age are found in inland Texas, much of the Gulf of Mexico, and the Caribbean, recording a huge tsunami perhaps several hundred feet (a hundred meters) high that was generated by the impact. The crater is at the center of a huge field of scattered spherules that extends across Central America and through the southern United States. The large structure is the right age to be the crater that resulted from the impact at the Cretaceous-Tertiary boundary, recording the extinction of the dinosaurs and other families.

The 66 million-year-old Deccan flood basalts, also known as traps, cover a large part of western India and the Seychelle Islands in the Indian Ocean. They are associated with the breakup of India from the Seychelles during the opening of the Indian Ocean. Slightly older flood basalts (90–83 million years old) are associated with the breaking away of Madagascar from India. The volume of the Deccan traps is estimated at 5,000,000 cubic miles (20,841,000 km^3), and the volcanics are thought to have erupted within about 1 million years, starting slightly before the great Cretaceous-Tertiary extinction. Most scientists now agree that the gases released during eruption of the flood basalts of the Deccan traps stressed the global biosphere to such an extent that many marine organisms had gone extinct, and many others were stressed. Then the massive Chicxulub impactor hit the planet, causing the massive extinction including the end of the dinosaurs. Faunal extinctions have been correlated with the eruption of the Deccan flood basalts at the Cretaceous-Tertiary (K-T) boundary. There is still considerable debate about the relative significance of flood basalt volcanism and impacts of meteorites for the K-T boundary. Most scientists would now agree, however, that the global environment was stressed shortly before the K-T boundary by volcanic-induced climate change, and then a huge meteorite hit the Yucatán Peninsula, forming the Chicxulub impact crater, causing the massive K-T boundary extinction and the death of the dinosaurs.

CENOZOIC TECTONICS AND CLIMATE

Cenozoic global tectonic patterns are dominated by the opening of the Atlantic Ocean, closure of the Tethys Ocean and formation of the Alpine-Himalayan Mountain System, and mountain building in western North America. Uplift of mountains and plateaus and the movement of continents severely changed oceanic and atmospheric circulation patterns, altering global climate patterns.

As the North and South Atlantic Oceans opened in the Cretaceous, western North America was experiencing contractional orogenesis. In the Paleocene (66–58 Ma) and Eocene (58–37 Ma), shallow dipping subduction beneath western North America caused uplift and basin formation in the Rocky Mountains, with arc-type volcanism resuming from later Eocene through late Oligocene (about 40–25 Ma). In the Miocene (starting at 24 Ma), the Basin and Range Province formed through crustal extension, and the formerly convergent margin in California was converted into a strike-slip or transform margin, causing the initial formation of the San Andreas fault.

The Cenozoic saw the final breakup of Pangaea and closure of the tropical Tethys Ocean between Eurasia and Africa, Asia, and India and a number of smaller fragments that moved northward from the southern continents. Many fragments of Tethyan Ocean floor (ophiolites) were thrust upon the continents during the closure of Tethys, including the Semail ophiolite (Oman), Troodos (Cyprus), and many Alpine bodies. Relative convergence between Europe and Africa, and Asia and Arabia plus India continues to this day, and is responsible for the uplift of the Alpine-Himalayan chain of mountains. The uplift of these mountains and the Tibetan Plateau has had important influences on global climate, including changes in the India Ocean monsoon and the cutting off of moisture that previously flowed across southern Asia. Vast deserts such as the Gobi were thus born.

The Tertiary began with generally warm climates, and nearly half of the world's oil deposits formed at this time. By the mid-Tertiary (35 Ma) the Earth began cooling again, and this culminated in the ice house climate of the Pleistocene, with many glacial advances and retreats. The Atlantic Ocean continued to open during the Tertiary, which helped lower global temperatures. The Pleistocene experienced many fluctuations between warm and cold climates, called glacial and interglacial stages (the Earth is currently in the midst of an interglacial stage). These fluctuations are rapid—for instance, in the past 1.5 million years the Earth has experienced 10 major and 40 minor periods of glaciation and interglaciation. The most recent glacial period peaked 18,000 years ago, when huge ice sheets covered most of Canada and the northern United States, and much of Europe.

The human species developed during the Holocene Epoch (since 10,000 years ago). The Holocene is just part of an extended interglacial period in the planet's current ice house event, raising important questions about how humans will survive if climate suddenly changes back to a glacial period. Since 18,000 years ago the climate has warmed by several degrees, sea level has risen 500 feet (150 m), and atmospheric CO_2 has increased. Some of the global warming is human induced. One scenario of climate evolution is that global temperatures will rise, causing some of the planet's ice caps to melt, raising the global sea level. This higher sea level may increase the Earth's reflectance of solar energy, suddenly plunging the planet into an ice house event and a new glacial advance.

See also CLIMATE; CLIMATE CHANGE; MASS EXTINCTIONS; PLATE TECTONICS.

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climate Climate refers to the average weather of a place or area and its variability over a period of years. The term *climate* is derived from the Greek work *klima,* meaning inclination and referring specifically to the angle of inclination of the Sun's rays, a function of latitude. The average temperature, precipitation, cloudiness, and windiness of an area determine its climate. Factors that influence climate include latitude; proximity to oceans or other large bodies of water that could moderate the climate; topography, which influences prevailing winds and may block precipitation; and altitude. All of these factors are linked together in the climate system of any region on the Earth. The global climate is influenced by many additional factors. The rotation of the Earth and latitudinal position determine where a place is located with respect to global atmospheric and oceanic circulation currents. Chemical interactions between seawater and magma significantly change the amount of carbon dioxide in the oceans and atmosphere and may change global temperatures. Pollution from humans also changes the amount of greenhouse gases in the atmosphere, which may be contributing to global warming. Climatology is the field of science concerned with climate, including both present-day and ancient climates. Climatologists study a variety of problems, ranging from the classification and effects of present-day climates through to the study of ancient rocks to determine ancient climates and their relationship to plate tectonics. An especially important field actively studied by climatologists is global climate change, with many studies focused on the effects that human activities have had and will continue to have on global climate. Many of these models require powerful supercomputers and computer models known as global circulation models. These models input various parameters at thousands or millions of grid points on a model Earth, and demonstrate how changing one or more variables (e.g., carbon dioxide, or CO_2, emissions) will affect the others.

Classifications of climate must account for the average, extremes, and frequencies of the different meteorological elements. Of the many different ways to classify climate, the most modern classifications are based on the early work of the German climatologist Wladimir Koppen. His classification (initially published in 1900) was based on the types of vegetation in an area, assuming that vegetation tended to reflect the average and extreme meteorological changes in an area. He divided the planet into different zones such as deserts, tropics, rain forest, tundra, and the like. In 1928 Norwegian meteorologist Tor Bergeron modified Koppen's classification to include the types of air masses that move through an area and how they influence vegetation patterns. The British meteorologist George Hadley made another fundamental understanding of the factors that influence global climate in the 18th century. Hadley proposed a simple, convective type of circulation in the atmosphere where heating by the Sun causes the air to rise near the equator and move poleward, where the air sinks back to the near surface, then returns to the equatorial regions. We now recognize a slightly more complex situation, in that there are three main convecting atmospheric cells in each hemisphere, named Hadley, Ferrel, and Polar cells. These play important roles in the distribution of different climate zones, as moist or rainy regions are located, in the tropics and at temperate latitudes, where the atmospheric cells are upwelling and release water. Deserts and dry areas are located around zones where the convecting cells downwell, bringing descending dry air into these regions.

The rotation of the Earth sets up systems of prevailing winds that modify the global convective atmospheric (and oceanic) circulation patterns. The spinning of the Earth sets up latitude-dependent airflow patterns, including the trade winds and westerlies. In addition, uneven heating of the Earth over land and ocean regions causes regional airflow patterns such as rising air over hot continents that must be replenished by air flowing in from the sides. The Coriolis force results from the rotation of the Earth and causes any moving air mass in the Northern Hemisphere to be deflected to the right and masses in the Southern Hemisphere to be deflected to the left. These types of patterns tend to persist for long periods of time and move large masses of air around the planet, redistributing heat and moisture and regulating the climate of any region.

Temperature, largely determined by latitude, is a major factor in the climate of any area. Polar regions experience huge changes in temperature between winter and summer months, largely a function of the wide variations in amount of incoming solar radiation and length of days. The proximity to large bodies of water such as oceans influences temperature, as water heats up and cools down much more slowly than land surfaces. Proximity to water therefore moderates temperature fluctuations. Altitude also influences temperature, with temperature decreasing with height.

Climate may change in cyclical or long-term trends, as influenced by changes in solar radiation, orbital variations of the Earth, amount of greenhouse gases in the atmosphere, or other phenomena such as El Niño or La Niña.

See also ATMOSPHERE; CLIMATE CHANGE; EL NIÑO AND THE SOUTHERN OSCILLATION (ENSO); GLACIER, GLACIAL SYSTEMS; GREENHOUSE EFFECT; ICE AGES; MILANKOVITCH CYCLES; PLATE TECTONICS; SEA-LEVEL RISE.

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climate change The Earth has experienced many episodes of dramatic climate change, with different periods in Earth history seeing the planet much hotter or much colder than the present. There have been periods when the entire planet was covered in ice in a frozen, seemingly perpetual winter, then other times the Earth's surface was scorchingly hot and dry, and others when much of the planet felt like a hot, wet sauna. Scientists, including those from the Intergovernmental Panel on Climate Change, warn that the planet is currently experiencing global warming at a rapid pace, and there will be significant consequences for the people and ecosystems on the planet, as explained in sections below.

Many different variables control climate and can change the planet rapidly from one condition to another. Most of these are related to variations in the amount of incoming solar radiation caused by astronomical variations in the Earth's orbit. Other variables that can strongly influence long-term climate change include the amount of heat retained by the atmosphere and oceans, and on timescales of tens to hundreds of millions of years, the distribution of landmasses as they move about the planet from plate tectonics. Each of these changes operates with different time cycles, alternately causing the climate to become warmer and colder.

Significant long-term climate changes include the gradual alteration of the Earth's atmosphere from a global hothouse dominated by carbon dioxide (CO_2) and other greenhouse gases when the Earth was young to an atmosphere rich in nitrogen and oxygen over the next couple billion years. Fortunately, during the early history of the Earth the Sun was less luminous, and the planet was not exceedingly hot. The motion of the continents has over time alternately placed them over the poles, which causes the continent to be covered in snow, reflecting more heat back to space and causing global cooling. Plate tectonics also has a complex interaction with concentrations of CO_2 in the atmosphere, for instance, by uplifting carbonate rocks to be exposed to the atmosphere during continental collisions. The calcium carbonate ($CaCO_3$) then combines with atmospheric CO_2, depositing it in the oceans. Thus continental collisions and times of supercontinent formation are associated with drawdown and reduction of CO_2 from the atmosphere, global cooling, and sea-level changes.

Orbital variations are the main cause of climate variations on more observable geological timescales.

The main time periods of these variations induce alternations of hotter and colder times, varying with frequencies of 100,000, 41,000, 23,000, and 19,000 years. To understand the complexity of natural climate variations, the contributions from each of these factors must be added together, forming a complex curve of climate warming and cooling trends. Built on top of these long-term climate variations that can change rapidly are shorter-term variations caused by changes in ocean circulation, sunspot cycles, and, finally, the contribution in the last couple of hundred years from the industry of humans, called anthropogenic changes. Deciphering which of these variables causes a particular percentage of the present global warming is no simple matter, and many political debates focus on who is to blame. Perhaps it is just as appropriate to focus on how we humans need to respond to global warming. Coastal cities may need to be moved, crop belts are migrating, climate zones are changing, river conditions will change, and many aspects of life that we are used to will be different. Scientists are expending considerable effort to understand the climate history of the past million years in order to predict the future.

NATURAL LONG-TERM CLIMATE CHANGE

Many controls operate to change the Earth's climate on different timescales. Some cause the global temperature to rise and fall within a time interval between warming and cooling influences of billions to hundreds of millions of years; others operate on time frames of millions to tens of millions of years. These slowly operating forces include the sluggish evolution of the composition of the planet's atmosphere from an early greenhouse atmosphere when the Earth had recently formed to its present-day composition. During the earliest history of the solar system, the Sun was about 30 percent less luminous, so the temperatures on Earth's surface were not as high as they could have been, given the early greenhouse conditions. Changes in solar luminosity have been significant in Earth history, and will be significant again in the future.

Plate tectonics exhibits different types of controls and with different timescales of influence on changing the atmospheric composition and climate. One type of influence of plate tectonics is on a planetary scale—plate tectonics goes through intervals of time in which seafloor spreading and volcanism is very active and periods when it is less active. During the active times the volcanism releases a lot of carbon dioxide and other greenhouse gases into the atmosphere, causing global warming. During inactive times global cooling can result. These changes operate on timescales of tens to hundreds of millions of years. Periods of very active seafloor spreading are often associated with periods of breakup of large continental landmasses known as supercontinents, and thus breakup of continents is often associated with global warming. Periods of less active seafloor spreading are often associated with continental amalgamations, formation of supercontinents, and global cooling.

When continents collide this process uplifts large sections of carbonate rocks from passive margins and exposes them to atmospheric weathering. When the calcium carbonate ($CaCO_3$) in these rocks is broken down by chemical weathering the carbonate ion (CO_3^{2-}) is dissolved by rainwater, and the free calcium ion (Ca^{2+}) then combines with atmospheric CO_2 to form new layers of limestone in the ocean, while drawing down CO_2 from the atmosphere and causing global cooling.

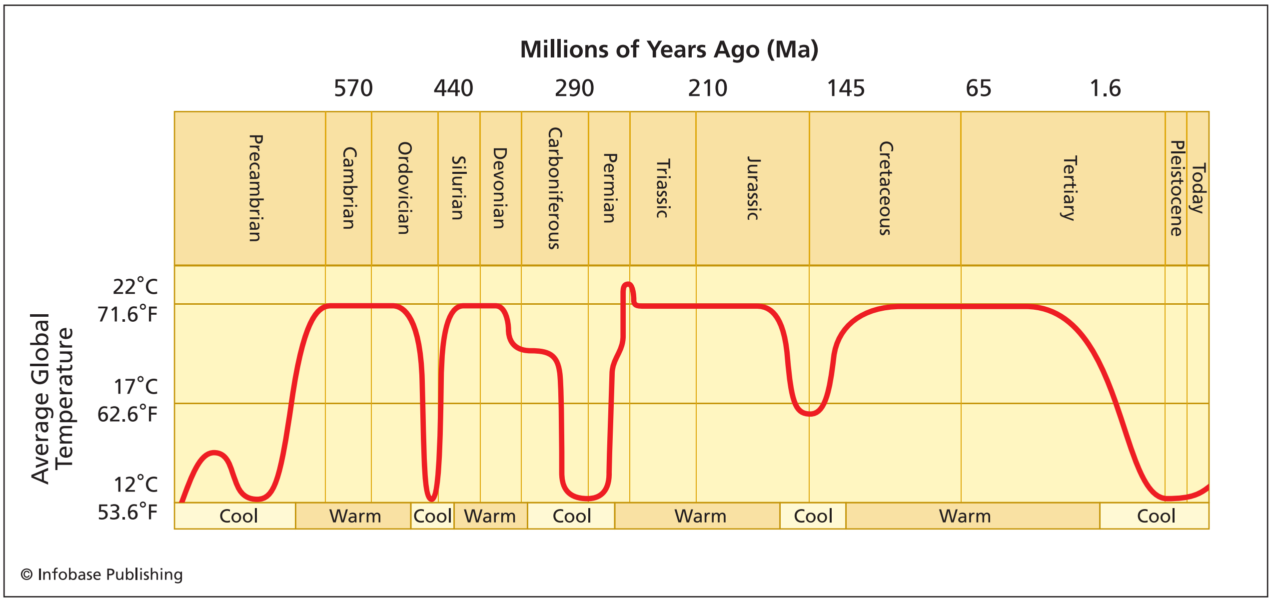
Scientists have shown that the interaction between these different long-term drivers of global climate is largely responsible for the long-term fluctuations in global climate on the billions to tens of millions of years timescales. Many aspects of these changes are not yet understood by geologists and paleoclimatologists, but the mechanisms described above seem fairly well understood and represent the most likely explanation for the causes of the changes.

Role of the Atmosphere in Climate Change

Interactions between the atmosphere, hydrosphere, biosphere, and lithosphere control global climate. Global climate represents a balance between the amount of solar radiation received and the amount of this energy retained in a given area. The planet receives about 2.4 times as much heat in the equatorial regions as in the polar regions. The atmosphere and oceans respond to this unequal heating by setting up currents and circulation systems that redistribute the heat more equally. These circulation patterns are in turn affected by the ever-changing pattern of the distribution of continents, oceans, and mountain ranges.

The amounts and types of gases in the atmosphere can modify the amount of incoming solar radiation, and hence global temperature. For instance, cloud cover can cause much of the incoming solar radiation to be reflected to space before being trapped by the lower atmosphere. On the other hand, greenhouse gases allow incoming short-wavelength solar radiation to enter the atmosphere, but trap this radiation when it tries to escape in its longer-wavelength reflected form. This causes a buildup of heat in the atmosphere and can lead to a phenomenon known as the greenhouse effect.

The amount of heat trapped in the atmosphere by greenhouse gases has varied greatly over Earth's history. One of the most important greenhouse gases



Plot showing how the average temperature on the surface of the Earth has changed with time over the past several hundreds of millions of years. These represent slow, long-term changes in global temperature.

is carbon dioxide (CO_2). Plants, which release oxygen gas (O_2) to the atmosphere, take up CO_2 during photosynthesis. In the early part of Earth's history (in the Precambrian, before plants covered the land surface), photosynthesis did not remove CO_2 from the atmosphere, with the result that CO_2 levels were much higher than at present. Marine organisms also take up atmospheric CO_2 by removing it from the ocean surface water (which is in equilibrium with the atmosphere) and use the CO_2 along with calcium to form their shells and mineralized tissue. These organisms make $CaCO_3$ (calcite is the most common mineral form of calcium carbonate), which is the main component of limestone, a rock composed largely of the dead remains of marine organisms. The atmosphere-ocean system presently has approximately 99 percent of the planet's CO_2 locked up in rock deposits of limestone on the continents and on the seafloor. If this amount of CO_2 were released back into the atmosphere, the global temperature would increase dramatically. In the early Precambrian, when this CO_2 was free in the atmosphere global temperatures averaged about 550°F (290°C).

The atmosphere redistributes heat quickly by forming and redistributing clouds and uncondensed water vapor around the planet along atmospheric circulation cells. Oceans are able to hold and redistribute more heat because of the greater amount of water in the oceans, but they redistribute this heat more slowly than the atmosphere. Surface currents are formed in response to wind patterns, but deep ocean currents that move more of the planet's heat follow courses that are more related to the bathymetry (topography of the seafloor) and the spinning of the Earth than they are related to surface winds.

The balance of incoming and outgoing heat from the Earth has determined the overall temperature of the planet through time. Examination of the geological record has enabled paleoclimatologists to reconstruct periods when the Earth had glacial periods, hot dry periods, hot wet periods, or cold dry periods. In most cases the Earth has responded to these changes by expanding and contracting its climate belts. Warm periods see an expansion of the warm subtropical belts to high latitudes, and cold periods see an expansion of the cold climates of the poles to low latitudes.

Plate Tectonics and Climate

The outer layers of the Earth are broken into about a dozen large tectonic plates, extending to about 60–100 miles (100–160 km) beneath the surface. Each of these plates may be made of oceanic crust and lithosphere, continental crust and lithosphere, or an oceanic plate with a continent occupying part of the area of the plate. Plate tectonics describes processes associated with the movement of these plates along three different types of boundaries: divergent, convergent, and transform. At divergent boundaries the plates move apart from one another, and molten rock (magma) rises from the mantle to fill the space between the diverging plates. This magma makes long ridges of volcanoes along a midocean ridge system that accounts for most of the volcanism on the planet. These volcanoes emit huge quantities of carbon dioxide (CO_2) and other gases when they erupt.

There have been times in the history of Earth that midocean ridge volcanism was very active, producing huge quantities of magma and CO_2 gas, and other times when the volcanism is relatively inactive. The large quantities of magma and volcanism involved in this process have ensured that variations in midocean ridge magma production have exerted strong controls on the amount of CO_2 in the atmosphere and ocean, and thus, are closely linked with climate. Periods of voluminous magma production are correlated with times of high atmospheric CO_2, and globally warm periods. These times are also associated with times of high sea levels, since the extra volcanic and hot oceanic material on the seafloor takes up extra volume and displaces the seawater to rise higher over the continents. This rise in sea levels in turn buried many rocks that are then taken out of the chemical weathering system, slowing down reactions between the atmosphere and the weathering of rocks. Those reactions are responsible for removing large quantities of CO_2 from the atmosphere, so the rise in sea level further promotes global warming during periods of active seafloor volcanism.

Convergent boundaries are places where two plates are moving toward each other or colliding. Most plate convergence happens where an oceanic plate is pushed or subducted beneath another plate, either oceanic or continental, forming a line of volcanoes on the overriding plate. This line of volcanoes is known as a magmatic arc, and specifically as an island arc if built on oceanic crust or an Andean arc if built on continental crust. When continents on these plates collide, the rocks that were deposited along their margins, typically underwater, are uplifted in the collision zone and exposed to weathering processes. The weathering of these rocks, particularly the limestone and carbonate rocks, causes chemical reactions where the CO_2 in the atmosphere reacts with the products of weathering, and forms new carbonate ($CaCO_3$) that gets deposited in the oceans. Continental collisions are thus associated with the overall removal of CO_2 from the atmosphere and help promote global cooling.

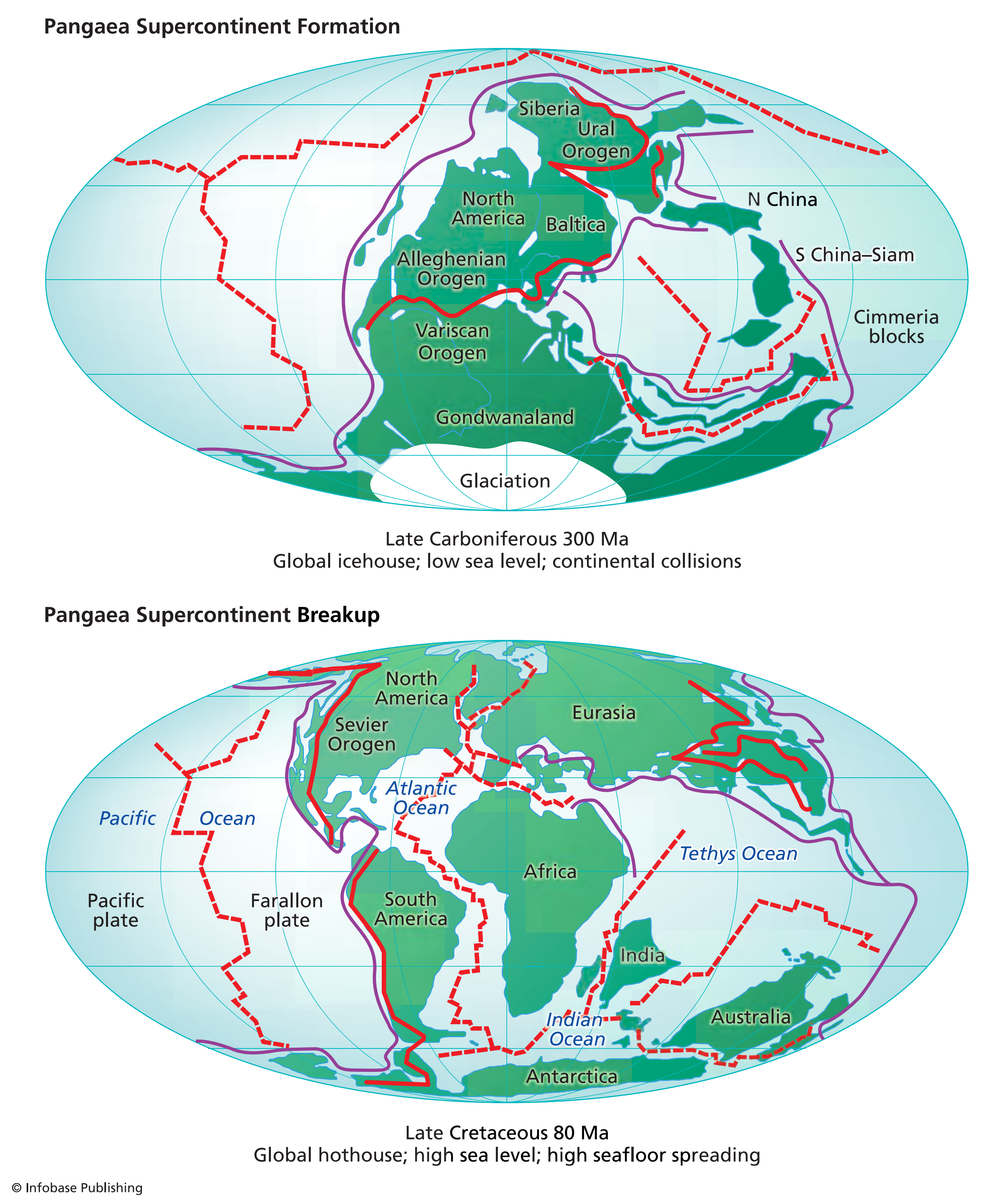
Transform margins do not significantly influence global climate since they are not associated with large amounts of volcanism, nor do they uplift large quantities of rock from the ocean.

The timescale of variations in global CO_2 related to changes in plate tectonics are slow, and they fall under the realm of causing very long-term climate changes, in cycles ranging from millions to tens of millions of years. Plate tectonics and movement of continents has been associated with glaciations for the past few billion years, but the exact link between tectonics and climate is not clearly established. Some doubt remains as to why global temperatures dropped, inducing the various glacial ages. The answer may be related to changes in the natural (nonbiogenic) production rate of carbon dioxide—the number one greenhouse gas. CO_2 is produced in volcanoes and in the midocean ridges, and it is lost by being slowly absorbed into the oceans. Both of these processes are very slow—about the right timescales to explain the Great Ice Ages. One theory is that more carbon dioxide is produced during times of faster-than-average rates of seafloor spreading and the subsequent increase in volcanism. During times of rapid spreading, the higher volcanic activity, coupled with higher sea levels and reduced chemical weathering of rocks, may promote global warming by enriching the CO_2 content of the atmosphere. Similarly, global cooling may result from stalled or slowed spreading.

Supercontinents and Climate

The motion of the tectonic plates periodically causes most of the continental landmasses of the planet to collide with each other, forming giant continents known as supercontinents. For much of the past several billion years, these supercontinents have alternately formed and broken up in a process called the supercontinent cycle. The last supercontinent was known as Pangaea, which broke up about 160 million years ago to form the present-day plates on the planet. Before that the previous supercontinent was Gondwana, which formed about 600–500 million years ago, and the one before that was Rodinia, formed around a billion years ago. The distribution of landmasses and formation and breakup of supercontinents has dramatically influenced global and local climate on timescales of 100 million years, with cycles repeating for the past few billion years of Earth's history. The supercontinent cycle predicts that the planet should have periods of global warming associated with supercontinent breakup, and global cooling associated with supercontinent formation. The supercontinent cycle affects sea-level changes, initiates periods of global glaciation, changes the global climate from hothouse to icehouse conditions, and influences seawater salinity and nutrient supply. All of these consequences of plate tectonics have profound influences on life on Earth.

Sea level has changed by thousands of feet (hundreds of meters) above and below current levels many times during Earth's history. In fact, sea level is constantly changing in response to a number of different variables, many of them related to plate tectonics, the supercontinent cycle, and climate. Sea level was 1,970 feet (600 m) higher than now during the Ordovician and reached a low stand at the end of the Permian. Sea levels were high again in the Cretaceous during the breakup of the supercontinent of Pangaea.



Pangaea Supercontinent Formation

Late Carboniferous 300 Ma
Global icehouse; low sea level; continental collisions

Pangaea Supercontinent Breakup

Late Cretaceous 80 Ma
Global hothouse; high sea level; high seafloor spreading

Maps of continental positions during cold and warm climates showing the relationship between climate and tectonics

Sea levels may change at different rates and amounts in response to different phases of the supercontinent cycle, and the sea level changes are closely related to climate. The global volume of the midocean ridges can change dramatically, either by increasing the total length of ridges or changing the rate of seafloor spreading. Either process produces more volcanism; increases the volume of volcanoes on the seafloor, raising sea levels; and puts a lot of extra CO_2 into the atmosphere, raising global temperatures. The total length of ridges typically increases during continental breakup, since continents are being rifted apart and some continental rifts can evolve into midocean ridges. Additionally, if seafloor spreading rates are increased, the amount of young, topographically elevated ridges is increased relative to the slower, older topographically lower ridges that occupy a smaller volume. If the volume of the ridges increases by either mechanism, then a volume of water equal to the increased ridge volume is displaced and sea level rises, inundating the continents. Changes in ridge volume are able to change sea levels positively or negatively by about 985 feet (300 m) from present values, at rates of about 0.4 inch (1 cm) every 1,000 years.

Continent-continent collisions, such as those associated with supercontinent formation, can lower sea levels by reducing the area of the continents. When continents collide, mountains and plateaus are uplifted, and the amount of material taken from below sea level to higher elevations no longer displaces seawater, causing sea levels to drop. The contemporaneous India-Asia collision has caused sea levels to drop by 33 feet (10 m). Times when supercontinents amalgamate are associated with times when seas drop to low levels.

Other factors, such as midplate volcanism, can also change sea levels. The Hawaiian Islands are hot-spot-style midplate volcanoes that have been erupted onto the seafloor, displacing an amount of water equal to their volume. Although this effect is not large at present, at some periods in Earth's history there were many more hot spots (such as in the Cretaceous), and the effect may have been larger.

The effects of the supercontinent cycle on sea level may be summarized as follows. Continent assembly favors regression, whereas continental fragmentation and dispersal favors transgression. Regressions followed formation of the supercontinents of Rodinia and Pangaea, whereas transgressions followed the fragmentation of Rodinia, and the Jurassic-Cretaceous breakup of Pangaea.

Climate and Seasonality

Variations in the average weather at different times of the year are known as seasons, controlled by the average amount of solar radiation received at the surface in a specific place for a certain time. Several factors determine the amount of radiation received at a particular point on the surface, including the angle at which the Sun's rays hit the surface, the length of time the rays warm the surface, and the distance to the Sun. As the Earth orbits the Sun approximately once every 365 days, it follows an elliptical orbit that brings it closest to the Sun in January (91 million miles, or 147 million kilometers) and farthest from the Sun in July (94.5 million miles, or 152 million kilometers). Therefore the Sun's rays are slightly more intense in January than in July but, as any Northern Hemisphere resident can testify, this must not be the main controlling factor determining seasonal warmth since winters in the Northern Hemisphere are colder than summers. Where the Sun's rays hit a surface directly, at right angles to the surface, they are most effective at warming the surface since they are not being spread out over a larger area on an inclined surface. Also, where the Sun's rays enter the atmosphere directly, they travel through the least amount of atmosphere, so are weakened much less than rays that must travel obliquely through the atmosphere, which absorbs some of their energy. The Earth's rotational axis is presently inclined at 23.5° from perpendicular to the plane on which it rotates around the Sun (the ecliptic plane), causing different hemispheres of the planet to be tilted toward or away from the Sun during different seasons. During the Northern Hemisphere summer the Northern Hemisphere is tilted toward the Sun, so it receives more direct sunlight rays than the Southern Hemisphere, causing more heating in the north than in the south. Also, since the Northern Hemisphere is tilted toward the Sun in summer, it receives direct sunlight for longer periods of time than the Southern Hemisphere, enhancing this effect. On the summer solstice on June 21, the Sun's rays are directly hitting 23.5°N latitude (called the tropic of Cancer) at noon. Because of the tilt of the planet, the Sun does not set below the horizon for all points north of the Arctic Circle (66.5°N). Points farther south have progressively shorter days, and points farther north have progressively longer days. At the North Pole the Sun rises above the horizon on March 20 and does not set again until six months later, on September 22. Since the Sun's rays are so oblique in these northern latitudes, however, they receive less solar radiation than areas farther south where the rays hit more directly but for shorter times. As the Earth rotates around the Sun, it finds the Southern Hemisphere tilted at its maximum amount toward the Sun on December 21 (summer solstice in the southern hemisphere), and the situation is reversed from the Northern Hemisphere summer, so that the same effects occur in the southern latitudes.

Seasonal variations in temperature and rainfall at specific places are complicated by global atmospheric circulation cells, proximity to large bodies of water and warm or cold ocean currents, and monsoon-type effects in some parts of the world. Seasons in some places are hot and wet, others are hot and dry, cold and wet, or cold and dry.

Supercontinents affect the supply of nutrients to the oceans and thus seasonality. Large supercontinents that contain most of the planet's landmass cause increased seasonality, and thus lead to an increase in the nutrient supply through overturning of the ocean waters. During breakup and dispersal, smaller continents have less seasonality, yielding decreased vertical mixing, leaving fewer nutrients in shelf waters. Seafloor spreading also increases the nutrient supply to the ocean; the more active the seafloor spreading system, the more interaction there is between ocean waters and crustal minerals that dissolve to form nutrients in the seawater.

NATURAL MEDIUM AND SHORT-TERM CLIMATE CHANGE

Plate tectonics, supercontinents, and massive volcanism can cause climate variations on timescales of millions to billions of years. Many other variables contribute to climate variations that operate on shorter-term timescales, many of which are more observable. Variations in Earth's orbit around the Sun exhibit cyclic variations that alternately make Earth's climate warmer and colder at timescales ranging from 100,000 years down to 11,000 years. These cycles, known as Milankovitch cycles, have been convincingly shown to correlate with advances and retreats of the glaciers in the past few million years, and have operated throughout Earth history.

Changes in ocean circulation patterns caused by changes in seawater salinity and many other factors can dramatically change the pattern of heat distribution on the planet and global climate. Many ocean currents are driven by differences in temperature and salinity of ocean waters; these currents form a pattern of global circulation known as thermohaline circulation. Changes in patterns of thermohaline circulation can occur quite rapidly, perhaps even over 5–10 years, suddenly plunging warm continents into long, icy winters or warming frozen, ice-covered landscapes. Other changes in the ocean-atmosphere system also cause the local climate to change on 5–10-year timescales. The most dramatic of these is the El Niño-Southern Oscillation, which strongly affects the Pacific and the Americas but has influences worldwide.

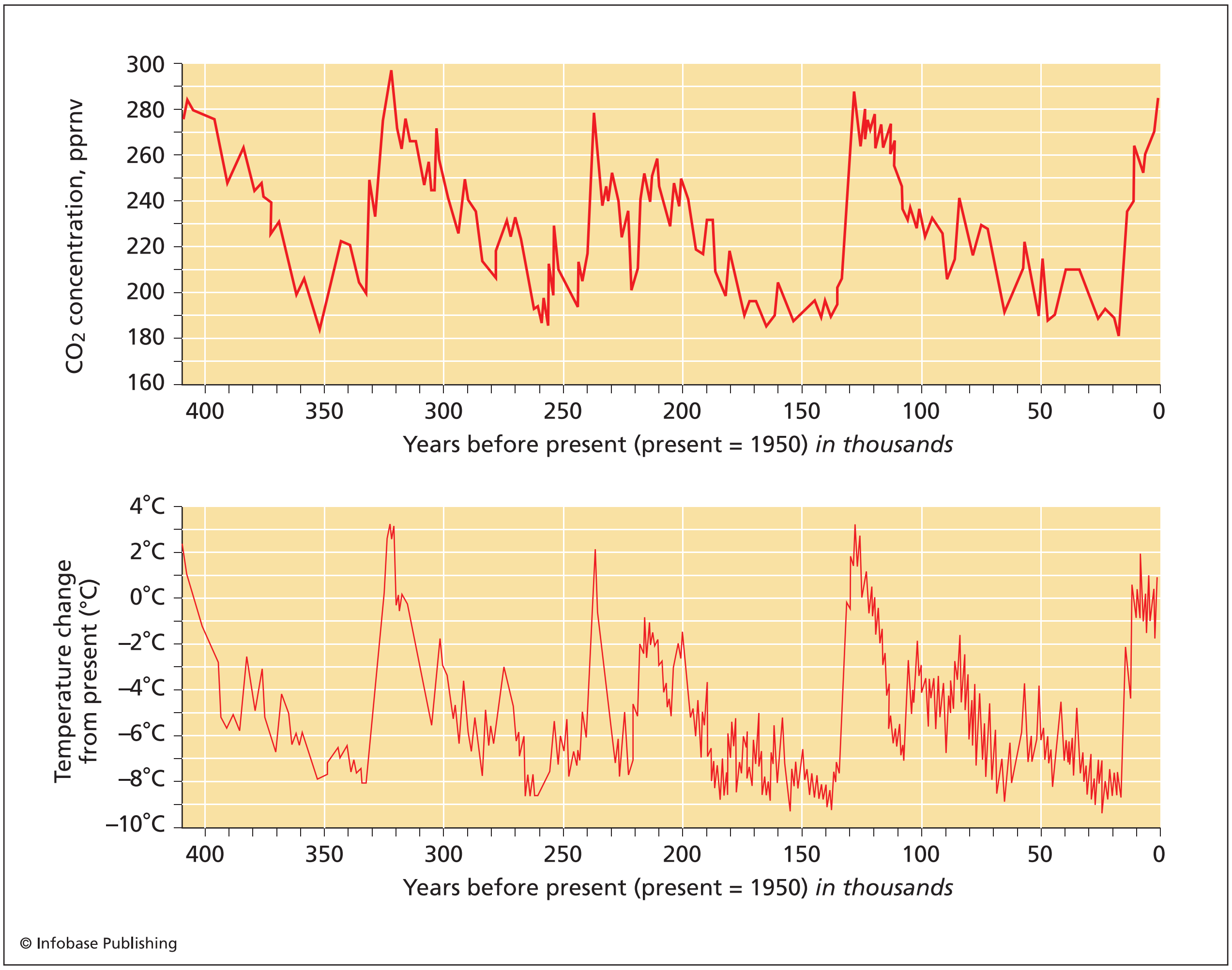
Astronomical Forcing of the Climate

Medium-term climate changes include those that alternate between warm and cold on timescales of 100,000 years or fewer. These medium-term climate changes include the semiregular advance and retreat of the glaciers during the many individual ice ages in the past few million years. Large global climate oscillations that have been recurring at approximately a 100,000-year periodicity at least for the past 800,000 years have marked the last 2.8 Ma. The warm periods, called interglacial periods, appear to last approximately 15,000 to 20,000 years before regressing to a cold ice age climate. The last of these major glacial intervals began ending about 18,000 years ago, as the large continental ice sheets covering North America, Europe, and Asia began retreating. The main climate events related to the retreat of the glaciers can be summarized as follows:

- 18,000 years ago: the climate begins to warm
- 15,000 years ago: advance of glaciers halts and sea levels begin to rise
- 10,000 years ago: Ice Age megafauna goes extinct
- 8,000 years ago: Bering Strait land bridge becomes drowned, cutting off migration of people and animals
- 6,000 years ago: the Holocene Maximum warm period
- So far in the past 18,000 years Earth's temperature has risen approximately 16°F (10°C), and sea level has risen 300 feet (91 m)

This past glacial retreat is but one of many in the past several million years, with an alternation of warm and cold periods apparently related to a 100,000-year periodicity in the amount of incoming solar radiation, causing the alternating warm and cold intervals. Systematic changes in the amount of incoming solar radiation, caused by variations in Earth's orbital parameters around the Sun, are known as Milankovitch cycles, after Milutin Milankovitch (1879–1958), a Serbian scientist who first clearly elucidated the relationships between the astronomical variations of the Earth orbiting the Sun and the climate cycles on Earth. These changes can affect many Earth systems, causing glaciations, global warming, and changes in the patterns of climate and sedimentation. Milankovitch's main scientific work was published by the Royal Academy of Serbia in 1941, during World War II. He calculated that the effects of orbital eccentricity, wobble, and tilt combine every 40,000 years to change the amount of incoming solar radiation, lowering temperatures and causing increased snowfall at high latitudes. His results have been widely used to interpret the climatic variations, especially in the Pleistocene record of ice ages, and also in the older rock record.

Astronomical effects influence the amount of incoming solar radiation; minor variations in the path of the Earth in its orbit around the Sun and the inclination or tilt of its axis cause variations in the amount of solar energy reaching the top of the atmosphere. These variations are thought to be responsible for the

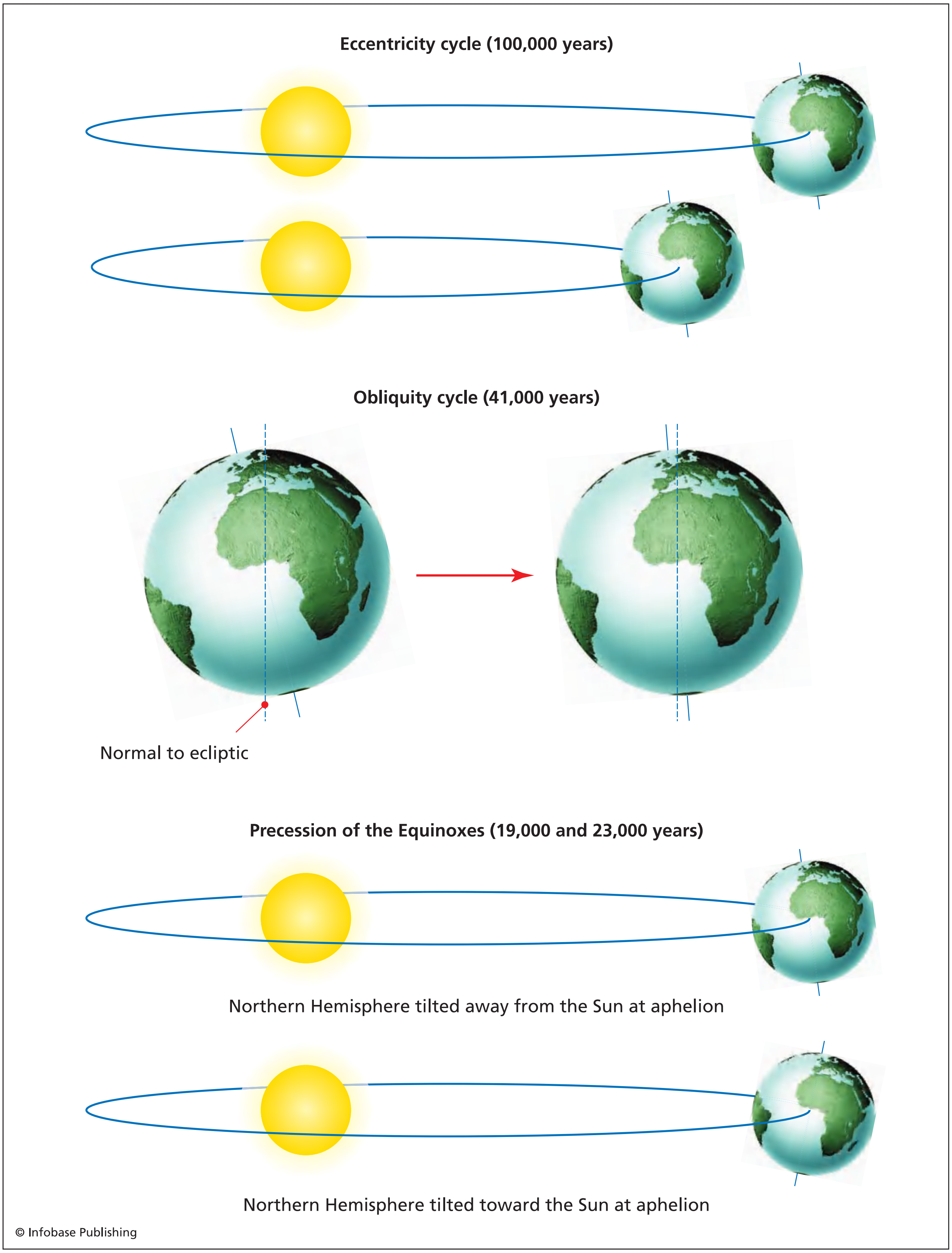


Temperature and CO$_2$ changes in past 400,000 years based on Antarctic ice cores

advance and retreat of the Northern and Southern Hemisphere ice sheets in the past few million years. In the past two million years alone the Earth has seen the ice sheets advance and retreat approximately 20 times. The climate record as deduced from ice-core records from Greenland and isotopic tracer studies from deep ocean, lake, and cave sediments suggest that the ice builds up gradually over periods of about 100,000 years, then retreats rapidly over a period of decades to a few thousand years. These patterns result from the cumulative effects of different astronomical phenomena.

Several movements are involved in changing the amount of incoming solar radiation. The Earth rotates around the Sun following an elliptical orbit, and the shape of this elliptical orbit is known as its eccentricity. The eccentricity changes cyclically with time with a period of 100,000 years, alternately bringing the Earth closer to and farther from the Sun in summer and in winter. This 100,000-year cycle is about the same as the general pattern of glaciers advancing and retreating every 100,000 years in the past 2 million years, suggesting that this is the main cause of variations within the present-day ice age. Presently the Earth's orbit is in a period of low eccentricity (~3 percent), and this yields a seasonal change in solar energy of ~7 percent. When the eccentricity is at its peak (~9 percent), "seasonality" reaches ~20 percent. In addition a more eccentric orbit changes the length of seasons in each hemisphere by changing the length of time between the vernal and autumnal equinoxes.

The Earth's axis is presently tilting by 23.5°N/S away from the orbital plane, and the tilt varies between 21.5°N/S and 24.5°N/S. The tilt, also known as obliquity, changes by plus or minus 1.5°N/S from a tilt of 23°N/S every 41,000 years. When the tilt is greater, there is greater seasonal variation in temperature. For small tilts winters would tend to be milder and summers cooler. This would lead to more glaciation.



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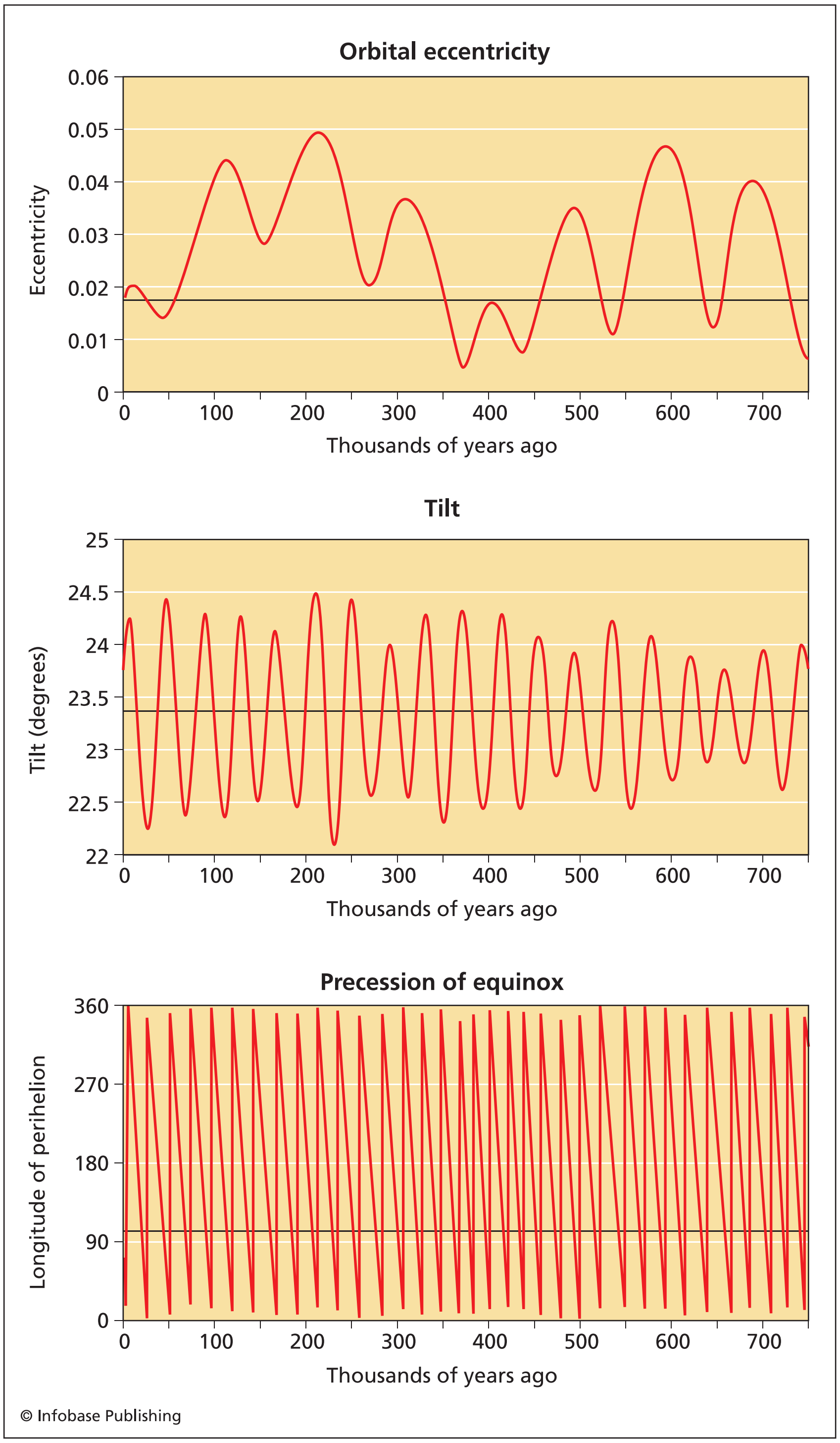
Orbital variations that lead to variation in the amount of incoming solar radiation, including eccentricity, obliquity (tilt), and precession of the equinoxes



Milankovitch cycles related to changes in eccentricity, obliquity (tilt), and precession of the equinoxes. All of these effects act together, and the curves need to be added to each other to obtain a true accurate curve of the climate variations because all these effects act at the same time.

Wobble of the rotation axis describes a motion much like a top rapidly spinning and rotating with a wobbling motion, such that the direction of tilt toward or away from the Sun changes, even though the tilt amount stays the same. This wobbling phenomenon is known as precession of the equinoxes, and it places different hemispheres closest to the Sun in different seasons. This precession changes with a double cycle, with periodicities of 23,000 years and 19,000 years. Presently the precession of the equinoxes is such that the Earth is closest to the Sun during the Northern Hemisphere winter. Due to precession the reverse will be true in ~11,000 years. This will give the Northern Hemisphere more severe winters.

Because each of these astronomical factors acts on different timescales, they interact in a complicated way (Milankovitch cycles, as described previously). Understanding these cycles, climatologists can make predictions of where the Earth's climate is heading, whether the planet is heading into a warming or cooling period, and whether populations need to plan for sea-level rise, desertification, glaciation, sea-level drop, floods, or droughts. When all the Milankovitch cycles (alone) are taken into account, the present trend should be toward a cooler climate in the Northern Hemisphere, with extensive glaciation. The Milankovitch cycles may help explain the advance and retreat of ice over periods of 10,000 to 100,000 years. They do not explain what caused the Ice Age in the first place.

The pattern of climate cycles predicted by Milankovitch cycles is further complicated by other factors that change the climate of the Earth. These include changes in thermohaline circulation, changes in the amount of dust in the atmosphere, changes caused by reflectivity of ice sheets, changes in concentration of greenhouse gases, changing characteristics of clouds, and even the glacial rebound of land that was depressed below sea level by the weight of glaciers.

Milankovitch cycles have been invoked to explain the rhythmic repetitions of layers in some sedimentary rock sequences. The cyclical orbital variations cause cyclical climate variations, which in turn are reflected in the cyclical deposition of specific types of sedimentary layers in sensitive environments. There are numerous examples of sedimentary sequences where stratigraphic and age control are sufficient to detect cyclical variation on the timescales of Milankovitch cycles; studies of these layers have proven consistent with a control of sedimentation by the planet's orbital variations. Some examples of Milankovitch-forced sedimentation have been documented from the Dolomite Mountains of Italy, the Proterozoic Rocknest Formation of northern Canada, and from numerous coral reef environments.

Predicting the future climate on Earth involves very complex calculations, including inputs from the long- and medium-term effects described in this entry, and some short-term effects such as sudden changes caused by human inputs of greenhouse gases into the atmosphere, and effects such as unpredicted volcanic eruptions. Nonetheless, most climate experts expect that the planet will continue to warm on the hundreds-of-years timescale. But judging by the recent geological past, we can reasonably expect that the planet could be suddenly plunged into another ice age, perhaps initiated by sudden changes in ocean circulation, following a period of warming. Climate is one of the major drivers of mass extinction, so the question remains whether the planet will be able to cope with rapidly fluctuating temperatures, dramatic changes in sea level, and enormous shifts in climate and agriculture belts.

Thermohaline Circulation and Climate

Variations in formation and circulation of ocean water may cause some of the thousands of years to decadal scale variations in climate. Cold water forms in the Arctic and Weddell Seas. This cold, salty water is denser than other water in the ocean, so it sinks to the bottom and gets ponded behind seafloor topographic ridges, periodically spilling over into other parts of the oceans. The formation and redistribution of North Atlantic cold bottom water accounts for about 30 percent of the solar energy budget input to the Arctic Ocean every year. Eventually this cold bottom water works its way to the Indian and Pacific Oceans, where it upwells, gets heated, and returns to the North Atlantic. Thermohaline circulation is the vertical mixing of seawater driven by density differences caused by variations in temperature and salinity. Variations in temperature and salinity are found in waters that occupy different ocean basins and those found at different levels in the water column. When the density of water at one level is greater than or equal to that below that level, the water column becomes unstable and the denser water sinks, displacing the deeper, less-dense waters below. When the dense water reaches the level at which it is stable, it tends to spread out laterally and form a thin sheet, causing intricately stratified ocean waters. Thermohaline circulation is the main mechanism responsible for the movement of water out of cold polar regions and exerts a strong influence on global climate. The upward movement of water in other regions balances the sinking of dense cold water, and these upwelling regions typically bring deep water, rich in nutrients, to the surface. Thus regions of intense biological activity are often associated with upwelling regions.

The coldest water on the planet is formed in the polar regions, with large quantities of cold water originating off the coast of Greenland and in the Weddell Sea of Antarctica. The planet's saltiest ocean water is found in the Atlantic Ocean, and this is moved northward by the Gulf Stream. As this water moves near Greenland it is cooled, then sinks to flow as a deep cold current along the bottom of the western North Atlantic. The cold water of the Weddell Sea is the densest on the planet, where surface waters are cooled to -35.4°F (-1.9°C), then sink to form a cold current that moves around Antarctica. Some of this deep cold water moves northward into all three major ocean basins, mixing with other waters and warming slightly. Most of these deep ocean currents move at a few to ten centimeters per second.

Presently, the age of bottom water in the equatorial Pacific is 1,600 years, and in the Atlantic it is 350 years. Glacial stages in the North Atlantic correlate with the presence of older cold bottom waters, approximately twice the age of the water today. This suggests that the thermohaline circulation system was only half as effective at recycling water during recent glacial stages, with less cold bottom water being produced during the glacial periods. These changes in production of cold bottom water may in turn be driven by changes in the North American ice sheet, perhaps itself driven by 23,000-year orbital (Milankovitch) cycles. Such a growth in the ice sheet would cause the polar front to shift southward, decreasing the inflow of cold saline surface water into the system required for efficient thermohaline circulation. Several periods of glaciation in the past 14,500 years (known as the Dryas) are thought to have been caused by sudden, even catastrophic injections of glacial meltwater into the North Atlantic, which would decrease the salinity and hence density of the surface water. This in turn would prohibit the surface water from sinking to the deep ocean, inducing another glacial interval.

Shorter-term decadal variations in climate in the past million years is indicated by so-called Heinrich Events, defined as specific intervals in the sedimentary record showing ice-rafted debris in the North Atlantic. These periods of exceptionally large iceberg discharges reflect that decadal-scale sea surface and atmospheric cooling are related to thickening of the North American ice sheet followed by ice-stream surges associated with the discharge of the icebergs. These events flood the surface waters with low-salinity freshwater, leading to a decrease in flux in the cold-bottom waters, and hence a short-period global cooling.

Changes in the thermohaline circulation rigor have also been related to other global climate changes. Droughts in the Sahel and elsewhere are correlated with periods of ineffective or reduced thermohaline circulation, because this reduces the amount of water drawn into the North Atlantic, in turn cooling surface waters and reducing the amount of evaporation. Reduced thermohaline circulation also reduces the amount of water that upwells in the equatorial regions, in turn decreasing the amount of moisture transferred to the atmosphere and reducing precipitation at high latitudes.

Atmospheric levels of greenhouse gases such as CO_2 and atmospheric temperatures show a correlation to variations in the thermohaline circulation patterns and production of cold-bottom waters. CO_2 is dissolved in warm surface water and transported to cold-surface water, which acts as a sink for the CO_2. During times of decreased flow from cold, high-latitude surface water to the deep ocean reservoir, CO_2 can build up in the cold polar waters, removing itself from the atmosphere and decreasing global temperatures. In contrast, when the thermohaline circulation is vigorous, cold oxygen-rich surface waters downwell, dissolving buried CO_2 and even carbonates, releasing this CO_2 into the atmosphere and increasing global temperatures.

The present-day ice sheet in Antarctica grew in the Middle Miocene, related to active thermohaline circulation that caused prolific upwelling of warm water that put more moisture in the atmosphere, falling as snow on the cold southern continent. The growth of the southern ice sheet increased the global atmospheric temperature gradients, which in turn increased the desertification of midlatitude continental regions. The increased temperature gradient also induced stronger oceanic circulation, including upwelling, removal of CO_2 from the atmosphere, lowering global temperatures, and bringing on late Neogene glaciations.

Ocean-bottom topography exerts a strong influence on dense bottom currents. Ridges deflect currents from one part of a basin to another and may restrict access to other regions, whereas trenches and deeps may focus flow from one region to another.

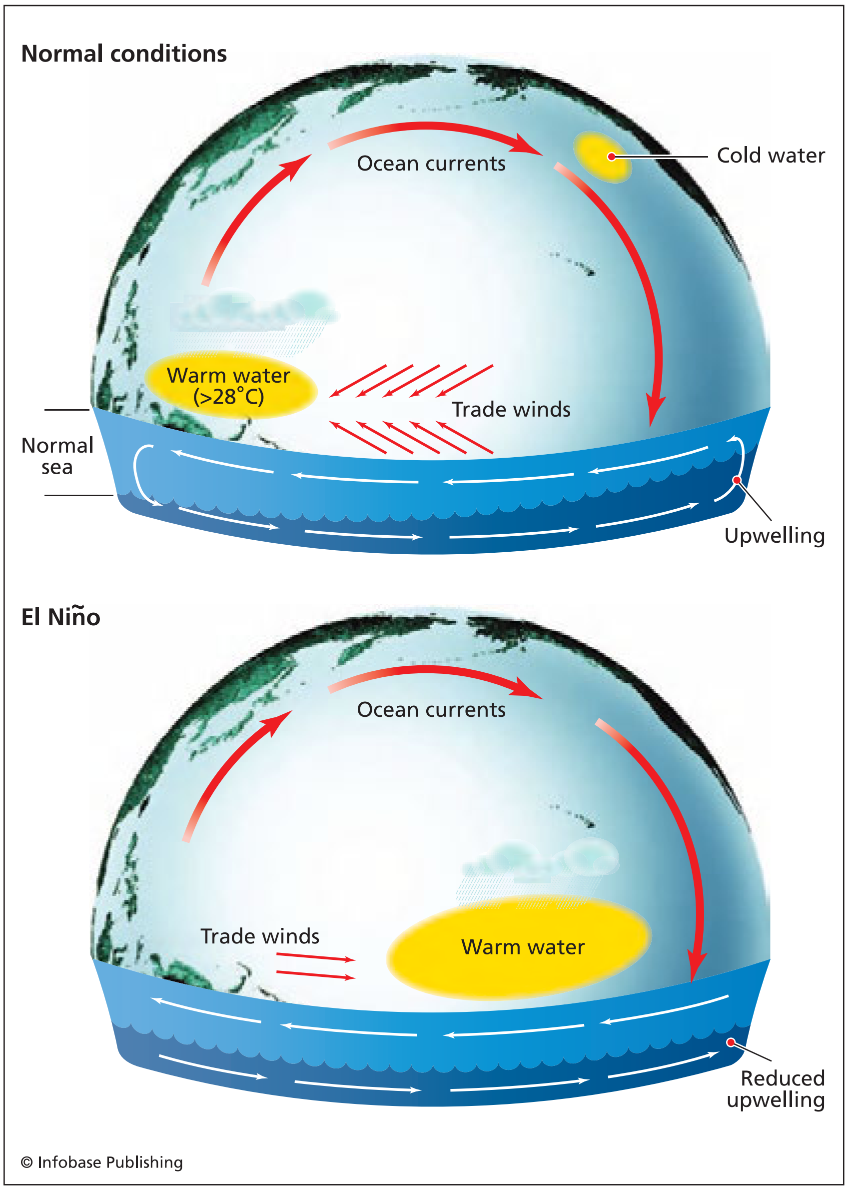
El Niño and the Southern Oscillation (ENSO)

El Niño–Southern Oscillation is the name given to one of the better-known variations in global atmospheric circulation patterns. Global oceanic and atmospheric circulation patterns undergo frequent shifts that affect large parts of the globe, particularly those arid and semiarid parts affected by Hadley Cell circulation. It is now understood that fluctuations in global circulation can account for natural disasters including the dust bowl days of the 1930s in the midwestern United States. Similar global climate fluctuations may explain the drought, famine, and desertification of parts of the Sahel, and the great famines of Ethiopia and Sudan in the 1970s and 1980s.

The secondary air circulation phenomenon known as the El Niño-Southern Oscillation can also profoundly influence the development of drought conditions and desertification of stressed lands. Hadley cells migrate north and south with summer and winter, shifting the locations of the most intense heating. Several zonal oceanic-atmospheric feedback systems influence global climate, but the most influential is the Austro-Asian system. In normal Northern Hemisphere summers the location of the most intense heating in Austral-Asia shifts from equatorial regions to the Indian subcontinent along with the start of the Indian monsoon. Air is drawn onto the subcontinent, where it rises and moves outward to Africa and the central Pacific. In Northern Hemisphere winters the location of this intense heating shifts to Indonesia and Australia, where an intense low-pressure system develops over this mainly maritime region. Air is sucked in, moves upward, and flows back out at tropospheric levels to the east Pacific. High pressure develops off the coast of Peru in both situations, because cold, upwelling water off the coast there causes the air to cool, inducing atmospheric downwelling. The pressure gradient set up causes easterly trade winds to blow from the coast of Peru across the Pacific to the region of heating, causing warm water to pile up in the Coral Sea off the northeast coast of Australia. This also causes the sea level to be slightly depressed off the coast of Peru, and more cold water upwells from below to replace the lost water. This positive-feedback mechanism is rather stable—it enhances the global circulation, as more cold water upwelling off Peru induces more atmospheric downwelling, and more warm water piling up in Indonesia and off the coast of Australia causes atmospheric upwelling in that region.

This stable linked atmospheric and oceanic circulation breaks down and becomes unstable every two to seven years, probably from some inherent chaotic behavior in the system. At these times, the Indonesian-Australian heating center migrates eastward, and the buildup of warm water in the western Pacific is no longer held back by winds blowing westward across the Pacific. This causes the elevated warm water mass to collapse and move eastward across the Pacific, where it typically appears off the coast of Peru by the end of December. The El Niño-Southern Oscillation (ENSO) events occur when this warming is particularly strong, with temperatures increasing by 40–43°F (22–24°C) and remaining high for several months. This phenomenon is also associated with a reversal of the atmospheric circulation around the Pacific such that the dry downwelling air is located over Australia and Indonesia, and the warm upwelling air is located over the eastern Pacific and western South America.

The arrival of El Niño is not good news in Peru, since it causes the normally cold upwelling and nutrient-rich water to sink to great depths, and the fish either must migrate to better feeding locations or die. The fishing industry collapses at these times, as does the fertilizer industry that relies on the bird guano normally produced by birds (that eat fish and anchovies) that also die during El Niño events. Warm moist air replaces the normally cold dry air, and the normally dry or desert regions of coastal Peru receive torrential rains with associated floods, landslides, death, and destruction. Shoreline erosion is accelerated in El Niño events, because the warm water mass that moved in from across the Pacific raises sea levels by 4–25 inches (10–60 cm), enough to cause significant damage.



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Schematic diagrams of the different patterns of ocean and air circulation over the Pacific associated with El Niño and normal conditions

The end of ENSO events also leads to abnormal conditions, in that they seem to turn on the "normal" type of circulation in a much stronger way than is normal. The cold upwelling water returns off Peru with such a ferocity that it may move northward, flooding a 1–2° band around the equator in the central Pacific ocean with water that is as cold as 68°F (20°C). This phenomenon is known as *La Niña* ("the girl" in Spanish).

The alternation between ENSO, La Niña, and normal ocean-atmospheric circulation has profound effects on global climate and the migration of different climate belts on yearly to decadal timescales, and is thought to account for about a third of all the variability in global rainfall. ENSO events may cause flooding in the western Andes and southern California, and a lack of rainfall in other parts of South America, including Venezuela, northeastern Brazil, and southern Peru. It may change the climate, causing droughts in Africa, Indonesia, India, and Australia, and is thought to have caused the failure of the Indian monsoon in 1899 that resulted in regional famine with the deaths of millions of people. Recently, the seven-year cycle of floods on the Nile has been linked to ENSO events, and famine and desertification in the Sahel, Ethiopia, and Sudan can be attributed to these changes in global circulation as well.

Major Volcanic Eruptions and Climate Change

Some of the larger, more explosive volcanic eruptions that the planet has witnessed in the past few hundred years have ejected large amounts of ash and finer particles called aerosols into the atmosphere and stratosphere, and it may take years for these particles to settle down to Earth. They get distributed about the planet by high-level winds, and they block some of the Sun's rays, which lowers global temperatures. This happens because particles and aerosol gases in the upper atmosphere tend to scatter sunlight back to space, lowering the amount of incoming solar energy. In contrast, particles that get injected only into the lower atmosphere absorb sunlight and contribute to greenhouse warming. A side effect is that the extra particles in the atmosphere also produce more spectacular sunsets and rises, as does extra pollution in the atmosphere. These effects were readily observed after the 1991 eruption of Mount Pinatubo in the Philippines, which spewed more than 172 billion cubic feet (5 billion m^3) of ash and aerosols into the atmosphere, causing global cooling for two years after the eruption. Even more spectacularly, the 1815 eruption of Tambora in Indonesia caused three days of total darkness for approximately 300 miles (500 km) from the volcano, and it initiated the famous "year without a summer" in Europe, because the ash from this eruption lowered global temperatures by more than a degree.

The amounts of gases and small airborne particles released by large volcanic eruptions such as Pinatubo, and even Tambora, are dwarfed by the amount of material placed into the atmosphere during some of Earth's most massive eruptions, known as flood basalt events. No flood basalts have been formed on Earth for several tens of millions of years, which is a good thing, since their eruption may be associated with severe changes in climate.

Scattered around the globe are numerous anomalously thick accumulations of dark lava, variously known as flood basalts, traps, or large igneous provinces. These vast outpourings of lava have different ages and represent the largest known volcanic episodes on the planet in the past several hundred million years. These deposits include continental flood basalt provinces, anomalously thick and topographically high seafloor known as oceanic plateaus, and some volcanic rifted passive margins. During eruption of these vast piles of volcanic rock, the Earth moved more material and energy from its interior in extremely short time periods than during the entire intervals between the massive volcanic events. Such large amounts of volcanism also released large amounts of volcanic gases into the atmosphere, with serious implications for global temperatures and climate, and may have contributed to some global mass extinctions. Many are associated with periods of global cooling where volcanic gases reduce the amount of incoming solar radiation and thereby bring on volcanic winters.

The largest continental flood basalt province in the United States is the Columbia River flood basalt in Washington, Oregon, and Idaho. The Columbia River flood basalt province is 6–17 million years old and contains an estimated 1,250 cubic miles (5,210 km^3) of basalt. Individual lava flows erupted through fissures or cracks in the crust, then flowed laterally across the plain for up to 400 miles (644 km).

The 66 million-year-old Deccan flood basalts, also known as traps, cover a large part of western India and the Seychelles. They are associated with the breakup of India from the Seychelles during the opening of the Indian Ocean. Slightly older flood basalts (90–83 million years) are associated with the break away of Madagascar from India. The volume of the Deccan traps is estimated at 5,000,000 cubic miles (20,840,000 km^3), and the volcanics are thought to have been erupted in about 1 million years, starting slightly before the great Cretaceous-Tertiary extinction. Most experts now agree that the gases released during this period of flood basalt volcanism aggravated the global biosphere to such an extent that many marine organisms were forced into extinction, and many others were stressed. Then the planet was hit by the meteorite that formed the massive Chicxulub impact crater on the Yucatán Peninsula (Mexico), causing the mass extinction including the end of the dinosaurs.

The breakup of east Africa along the East African rift system and the Red Sea is associated with large amounts of Cenozoic (fewer than 30 million years old) continental flood basalts. Some of the older volcanic fields are located in east Africa in the Afar region of Ethiopia, south into Kenya and Uganda, and north across the Red Sea and Gulf of Aden into Yemen and Saudi Arabia. These volcanic piles are overlain by younger (fewer than 15 million year old) flood basalts that extend both farther south into Tanzania and farther north through central Arabia, where they are known as Harrats, and into Syria, Israel, Lebanon, and Jordan.

An older volcanic province also associated with the breakup of a continent is known as the North Atlantic Igneous Province. It formed along with the breakup of the North Atlantic Ocean at 62–55 million years ago, and includes both onshore and offshore volcanic flows and intrusions in Greenland, Iceland, and the northern British Isles, including most of the Rockall Plateau and Faeroes Islands. In the south Atlantic a similar 129–134 million-year-old flood basalt was split by the opening of the ocean, and now has two parts. In Brazil the flood lavas are known as the Paraná basalts, and in Namibia and Angola of west Africa as the Etendeka basalts.

The Caribbean Ocean floor is one of the best examples of an oceanic plateau, with other major examples including the Ontong-Java Plateau, Manihiki Plateau, Hess Rise, Shatsky Rise, and Mid Pacific Mountains. All of these oceanic plateaus contain between six- and 25-mile thick piles of volcanic and subvolcanic rocks representing huge outpourings of lava. The Caribbean seafloor preserves 5–13 mile (8–21 km) thick oceanic crust formed before about 85 million years ago in the eastern Pacific Ocean. This unusually thick ocean floor was transported eastward by plate tectonics, where pieces of the seafloor collided with South America as it passed into the Atlantic Ocean. Pieces of the Caribbean oceanic crust are now preserved in Colombia, Ecuador, Panama, Hispaniola, and Cuba, and some scientists estimate that the Caribbean oceanic plateau may have once been twice its present size. In either case it represents a vast outpouring of lava that would have been associated with significant outgassing, with possible consequences for global climate and evolution.

The western Pacific Ocean basin contains several large oceanic plateaus, including the 20-mile (32-km) thick crust of the Alaskan-sized Ontong-Java Plateau, the largest outpouring of volcanic rocks on the planet. It apparently formed in two intervals, at 122 and 90 million years ago, respectively, entirely within the ocean, and represents magma that rose in a plume from deep in the mantle and erupted on the seafloor. It is estimated that the volume of magma erupted in the first event was equivalent to that of all the magma being erupted at midocean ridges at the present time. Sea levels rose by more than 30 feet (9 m) in response to this volcanic outpouring. The gases released during these eruptions are estimated to have raised average global temperatures by 23°F (13°C).

Examples of Climate Changes Caused by Flood Basalt Volcanism

The environmental impact of the eruption of large volumes of basalt can be severe. Huge volumes of sulfur dioxide, carbon dioxide, chlorine, and fluorine are released during large basaltic eruptions. Much of this gas may get injected into the upper troposphere and lower stratosphere during the eruption process, being released from eruption columns that reach 2–8 miles (3–13 km) in height. Carbon dioxide, a greenhouse gas, can cause global warming, whereas sulfur dioxide (and hydrogen sulfate) has the opposite effect and can cause short-term cooling. Many of the episodes of volcanism preserved in these large igneous provinces were rapid, repeatedly releasing enormous quantities of gases over periods of fewer than 1 million years, and released enough gas to change significantly the climate more rapidly than organisms could adapt. For instance, one eruption of the Columbia River basalts is estimated to have released 9,000 million tons of sulfur dioxide, and thousands of millions of tons of other gases, compared with the eruption of Mount Pinatubo in 1991, which released about 20 million tons (18 million tonnes) of sulfur dioxide.

The Columbia River basalts of the Pacific Northwest are instructive about how flood basalts can influence climate. These lavas continued erupting for years at a time, for approximately a million years. During this time the gases released would be equivalent to that of Mt. Pinatubo, every week, over periods maintained for decades to thousands of years at a time. The atmospheric consequences are sobering. Sulfuric acid aerosols and acid from the fluorine and chlorine would form extensive poisonous acid rain, destroying habitats and making waters uninhabitable for some organisms. At the very least the environmental consequences would be such that organisms were stressed to the point that they would not be able to handle an additional environmental stress, such as a global volcanic winter and subsequent warming caused by a giant impact.

Mass extinctions have been correlated with the eruption of the Deccan flood basalts at the Cretaceous-Tertiary (K/T) boundary, and with the Siberian flood basalts at the Permian-Triassic boundary. There is still considerable debate about the relative significance of flood basalt volcanism and impacts of meteorites for extinction events, particularly at the Cretaceous-Tertiary boundary. However, most scientists would now agree that global environment was stressed shortly before the K/T boundary by volcanic-induced climate change, and then a huge meteorite hit the Yucatán Peninsula, forming the Chicxulub impact crater, causing the massive K/T boundary extinction and the death of the dinosaurs.

The Siberian flood basalts cover a large area of the Central Siberian Plateau northwest of Lake Baikal. They are more than half a mile (1 km) thick over an area of 210,000 square miles (543,900 km^2) but have been significantly eroded from an estimated volume of 1,240,000 cubic miles (3,211,600 km^3). They were erupted over an extraordinarily short period of fewer than 1 million years 250 million years ago, at the Permian-Triassic boundary. They are remarkably coincident in time with the major Permian/Triassic extinction, implying a causal link. The Permian/Triassic boundary at 250 million years ago marks the greatest extinction in Earth history, where 90 percent of marine species and 70 percent of terrestrial vertebrates became extinct. It has been postulated that the rapid volcanism and degassing released enough sulfur dioxide to cause a rapid global cooling, inducing a short ice age with associated rapid fall of sea level. Soon after the ice age took hold, the effects of the carbon dioxide took over and the atmosphere heated to cause global warming. The rapidly fluctuating climate postulated to have been caused by the volcanic gases is thought to have killed off many organisms that were simply unable to cope with the wildly fluctuating climate extremes.

The close relationship between massive volcanism and changes in climate that have led to mass extinctions shows how quickly life on Earth can change. The effects of massive global volcanism are much greater than any changes so far caused by humans, and operate faster than other plate tectonic and supercontinent-related changes.

How Fast Can Climate Change

Understanding how fast climate can shift from a warm period to a cold, or cold to a warm, is difficult. The record of climate indicators is incomplete and difficult to interpret. Only 18,000 years ago the planet was in the midst of a major glacial interval, and since then global average temperatures have risen 16°F (10°C) and are still rising, perhaps at a recently accelerated rate from human contributions to the atmosphere. Still, recent climate work is revealing that there are some abrupt transitions in the slow warming, in which there are major shifts in some component of the climate, where the shift may happen on scales of 10 years or fewer.

One of these abrupt transitions seems to affect the circulation pattern in the North Atlantic Ocean, where the ocean currents formed one of two different stable patterns or modes, with abrupt transitions occurring when one mode switches to the other. In the present pattern the warm waters of the Gulf Stream come out of the Gulf of Mexico and flow along the eastern seaboard of the United States, part of the British Isles, to the Norwegian Sea. This warm current is largely responsible for the mild climate of the British Isles and northern Europe. In the second mode the northern extension of the Gulf Stream is weakened by a reduction in salinity of surface waters from sources at high latitudes in the North Atlantic. The fresher water has a source in increased melting from the polar ice shelf, Greenland, and northern glaciers. With less salt, seawater is less dense and less able to sink during normal wintertime cooling.

Studies of past switches in the circulation modes of the North Atlantic reveal that the transition from one mode of circulation to the other can occur over a period of only five to 10 years. These abrupt transitions are apparently linked to increase in the release of icebergs and freshwater from continental glaciers, which upon melting contribute large volumes of freshwater into the North Atlantic, systematically reducing the salinity. The Gulf Stream presently seems on the verge of failure, or of switching modes from mode 1 to 2, and historical records show that this switch can be very rapid. If this predicted switch occurs, northern Europe and the United Kingdom may experience a significant and dramatic cooling of their climate, instead of the warming many fear.

See also ATMOSPHERE; CARBON CYCLE; CLIMATE; GLOBAL WARMING; GREENHOUSE EFFECT; ICE AGES; METEOROLOGY; MILANKOVITCH CYCLES; PALEOCLIMATOLOGY; SEA-LEVEL RISE; THERMOHALINE CIRCULATION.

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Cloud, Preston (1912–1991) **American *Historical Geologist, Geobiologist*** Preston Ercelle Cloud Jr. was an eminent geobiologist and paleontologist who contributed important observations and interpretations that led to greater understanding of the evolution of the atmosphere, oceans, and crust of the Earth, and most important, to understanding the evolution of life on the planet.

Born in West Upton, Massachusetts, on September 26, 1912, as a child Cloud moved to Waynesboro, Pennsylvania, where he developed a keen sense of the outdoors and the rolling hills of the Appalachians. He joined the U.S. Navy from 1930 to 1933, then enrolled in George Washington University in Washington, D.C., where he cultivated contacts at the

National Museum of Natural History. As an undergraduate student Cloud developed a solid knowledge of paleontology, learning much especially about brachiopods from the collections at the National Museum in Washington, D.C.

Preston Cloud continued his education at Yale University and received a Ph.D. in 1940 for a study of Paleozoic brachiopods. From there he moved to Missouri School of Mines in Rolla, but then returned to Yale as a Research Fellow from 1941 to 1942. During World War II Cloud was called to duty with the U.S. Geological Survey, where he worked with the wartime strategic minerals program, first mapping manganese deposits in Maine, then investigating bauxite in Alabama. After this Cloud studied the Ellenburger Limestone—an important oil reservoir—from the Lower Paleozoic section of Texas, and made accurate descriptions of the stratigraphic and paleontologic relationships in this unit.

In 1946 Cloud took a position as an assistant professor of paleontology at Harvard University but in 1948 returned to the U.S. Geological Survey to map parts of Saipan Island in the Mariana Islands in the Pacific. This work led him to publish many papers on modern carbonate and coral reef systems, including his landmark works on evolution, in which he proposed that complex, multicellular organisms evolved from many different ancestors about 700 million years ago. Through his studies of geochemical processes Cloud linked the rapid evolution of these species to a change in atmospheric chemistry in which the oxygen levels in the atmosphere climbed rapidly, helping the organisms expand into available ecological niches. Cloud was promoted to chief paleontologist with the U.S. Geological Survey from 1949 to 1959, and the department grew dramatically under his guidance.

After he resigned as head paleontologist at the survey, Cloud studied the continental shelves and coastal zone, expanding the knowledge of these regions dramatically and leading to oil exploration on the continental shelves. He then accepted a job as chairman of the Department of Geology and Geophysics at the University of Minnesota, and organized a new multidisciplinary approach to earth sciences by forming the School of Earth Sciences. While at Minnesota Cloud concentrated on the Precambrian and the first 86 percent of Earth history, the origin and development of life, and studied Precambrian outcrops from around the world in this context. Cloud became world-famous for his studies of Precambrian carbonate rocks and their fossil assemblages, which consist mostly of stromatolites, and ideas about the origin and evolution of life.

In 1965 Cloud moved to the University of California, Los Angeles, then in 1968 he moved to the Santa Barbara campus. In 1979 he retired but remained active in publishing books on life on the planet, and was also active on campus. Preston Cloud emphasized complex interrelationships among biological, chemical, and physical processes throughout Earth history. His work expanded beyond the realm of rocks and fossils, and he wrote about the limits of the planet for sustaining the exploding human population. He recognized that limited material, food, and energy resources with the expanding human activities could lead the planet into disaster. One of his most famous works in this field was his *Oasis in Space*. Cloud was elected a member of the Academy of Sciences and was active for 30 years. In 1976 Preston Cloud was awarded the Penrose Medal by the Geological Society of America, and in 1977 he was awarded the Charles Doolittle Walcott Medal by the National Academy of Sciences. The Preston Cloud Laboratory at the University of California, Santa Barbara, is dedicated to the study of pre-Phanerozoic life on Earth.

See also HISTORICAL GEOLOGY; PALEONTOLOGY, SEDIMENTARY ROCK, SEDIMENTATION.

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clouds Clouds are visible masses of water droplets or ice crystals suspended in the lower atmosphere, generally confined to the troposphere. The water droplets and ice crystals condense from water vapor around small dust, pollen, salt, ice, or pollution particles that aggregate into cloud formations, classified according to their shape and height in the atmosphere. Luke Howard, an English naturalist, suggested the classification system still widely used today in 1803. He suggested Latin names based on 10 genera, then further divided into species. In 1887 the British naturalist Ralph Abercromby and H. Hildebrand Hildebrandsson of Sweden further divided the clouds into high, middle, and low-level types, as well as clouds that form over significant vertical distances. The basic types of clouds include the heaped cumulus, layered stratus, and wispy cirrus. If rain is falling from a cloud, the term *nimbus* is added, as in cumulonimbus, the common thunderhead cloud.

High clouds form above 19,685 feet (6,000 m) and are generally found at mid to low latitudes.

The air at this elevation is cold and dry, so the clouds consist of ice crystals, and appear white to the observer on the ground except at sunrise and sunset. The most common high clouds are the cirrus—thin, wispy clouds typically blown into thin, horsehairlike streamers by high winds. Prevailing high-level winds blow most cirrus clouds from west to east, a sign of generally good weather. Cirrocumulus clouds are small, white puffy clouds that sometimes line up in ripplelike rows and at other times form individually. Their appearance over large parts of the sky is often described as a Mackeral sky, because of the resemblance to fish scales. Cirrostratus are thin, sheetlike clouds that typically cover the entire sky. They are so thin that the Sun, Moon, and some stars can be seen through them. They are composed of ice crystals, and light that refracts through these clouds often forms a halo or sun dogs. These high clouds often form in front of an advancing storm and typically foretell of rain or snow in 12–24 hours.

Middle clouds form between 6,560 and 22,965 feet (2,000 and 7,000 m), generally in middle latitudes. They are composed mostly of water droplets, with ice crystals in some cases. Altocumulus clouds are gray, puffy masses that often roll out in waves, with some parts appearing darker than others. Altocumulus are usually less than 0.62 miles (1 km) thick. They form with rising air currents at cloud level, and a morning appearance often predicts thunderstorms by late afternoon. Altostratus are thin, blue-gray clouds that often cover the entire sky, and the sun may shine dimly through, appearing as a faint, irregular disk. Altostratus clouds often form in front of storms that bring regional steady rain.

Cirrus clouds over coast range at Purisima Creek Redwoods, Bay Area, California *(NOAA/Department of Commerce)*

Low clouds have bases that may form below 6,650 feet (2,000 m) and are usually composed entirely of water droplets. In cold weather they may contain ice and snow. Nimbostratus are the dark gray, rather uniform-looking clouds associated with steady light to moderate rainfall. Rain from the nimbostratus clouds often causes the air to become saturated with water, and a group of thin, ragged clouds that move rapidly with the wind may form. These are known as stratus fractus, or scud clouds. Stratocumulus clouds are low, lumpy-looking clouds that form rows or other patterns, with clear sky visible between the cloud rows. The Sun may form brilliant streaming rays known as crepuscular rays through these clouds. Stratus clouds have a uniform gray appearance and may cover the sky, resembling fog but not touching the ground. They commonly appear near the seashore, especially in summer months.

Some clouds form over a significant range of atmospheric levels. Cumulus are flat-bottomed, puffy clouds with irregular, domal, or towering tops. Their bases may be lower than 3,280 feet (1,000 m). On warm summer days small cumulus clouds may form in the morning and develop significant vertical growth by the afternoon, creating a towering cumulus or cumulus congestus cloud. These may continue to develop further into the giant cumulonimbus, giant thunderheads with bases that may be as low as a few hundred meters, and tops extending to more than 39,370 feet (12,000 m) in the tropopause. Cumulonimbus clouds release tremendous amounts of energy in the atmosphere and may be associated with high winds, vertical updrafts and downdrafts, lightning, and tornadoes. The lower parts of these giant clouds are made of water droplets, the middle parts may contain both water and ice, whereas the tops may consist entirely of ice crystals.

Many types of unusual clouds form in different situations. Plieus clouds may form over rising cumulus tops, looking like a halo or fog around the cloud peak. Banner clouds form over and downwind of high mountain tops, sometimes resembling steam coming out of a volcano. Lenticular clouds form wavelike figures from high winds moving over mountains, and may form elongate, pancakelike shapes. Unusual and even scary-looking mammatus clouds form bulging, baglike sacks underneath some

Cumulus cloud over Arizona desert *(Aleksander Bochenek, Shutterstock, Inc.)*

cumulonimbus clouds, forming when the sinking air is cooler than the surrounding air. Mammatus-like clouds may also form underneath clouds of volcanic ash. Finally, jet airplanes produce condensation trails when water vapor from the jet's exhaust mixes with the cold air, which becomes suddenly saturated with water and forms ice crystals. Pollution particles from the exhaust may provide the nuclei for the ice. In dry conditions condensation, or con trails, will evaporate quickly, but in more humid conditions the con trails may persist as cirruslike clouds. With the growing numbers of jet flights in the past few decades, con trails have rapidly become a significant source of cloudiness, contributing to the global weather and perhaps climate.

Clouds greatly influence the Earth's climate. They efficiently reflect short-wavelength radiation from the Sun back into space, cooling the planet. But since they are composed of water, they also stop the longer-wavelength radiation from escaping, causing a greenhouse effect. Together these two apparently opposing effects of clouds strongly influence the climate of the Earth. In general the low- and middle-level clouds cool the Earth, whereas abundant high clouds tend to warm the Earth with the greenhouse effect.

See also ATMOSPHERE; CLIMATE; CLIMATE CHANGE; ENERGY IN THE EARTH SYSTEM.

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comet Comets are bodies of ice, dust, and rock that orbit the Sun and exhibit a coma (or atmosphere) extending away from the Sun as a tail when they are close to the Sun. They have orbital periods that range from a few years to a few hundred or even thousands of years. Short-period comets have orbital periods of fewer than 200 years, and most of these orbit in the plane of the ecliptic in the same direction as the planets. Their orbits take them past the orbit of Jupiter at aphelion, and near the Sun at perihelion. Long-period comets have highly elongated or eccentric orbits, with periods longer than 200 years and extending to thousands or perhaps even millions of years. These comets range far beyond the orbits of the outer planets, although they remain gravitationally bound to the Sun. Another class of comets, called single-apparition comets, have a hyperbolic trajectory that sends them past the inner solar system only once, then they are ejected from the solar system.

Before late 20th-century space probes collected data on comets, comets were thought to be composed primarily of ices and to be lone wanderers of the solar system. Now, with detailed observations, it is clear that comets and asteroids are transitional in nature, both in composition and in orbital character. Comets are now known to consist of rocky cores with ices around them or in pockets, and many have an organic-rich dark surface. Many asteroids are also made of similar mixtures of rocky material with pockets of ice. There are so many rocky/icy bodies in the outer solar system in the Kuiper belt and Oort Cloud that comets are now regarded as the most abundant type of bodies in the universe. There may be one trillion comets in the solar system, of which only about 3,350 have been cataloged. Most are long-period comets, but several hundred short-period comets are known as well.

The heads of comets can be divided into several parts, including the nucleus; the coma, or gaseous rim from which the tail extends; and a diffuse cloud of hydrogen. The heads of comets can be quite large, some larger than moons or other objects including Pluto. Most cometary nuclei range between 0.3 and 30 miles (0.5–50 km) in diameter and consist of a mixture of silicate rock, dust, water ice, and other frozen gases such as carbon monoxide, carbon dioxide, ammonia, and methane. Some comets contain a variety of organic compounds including methanol, hydrogen cyanide, formaldehyde, ethanol, and ethane, as well as complex hydrocarbons and amino acids. Although some comets have many organic molecules, no life is known to exist on or be derived from comets. These organic molecules make cometary nuclei some of the darkest objects in the universe, reflecting only 2–4 percent of the light that falls on their surfaces. This dark color may actually help comets absorb heat, promoting the release of gases to form the tail. Cometary tails can change in length, and can be 80 times larger than the head when the comet passes near the Sun.

As a comet approaches the Sun, it begins to emit jets of ices consisting of methane, water, and ammonia, and other ices. Modeling of the comet surface by astronomers suggests that the tails form when the radiation from the Sun cracks the crust of the comet and begins to vaporize the volatiles like carbon, nitrogen, oxygen, and hydrogen, carrying away dust from the comet in the process. The mixture of dust and gases emitted by the comet then forms a large but weak atmosphere around the comet, called the coma. The radiation and solar wind from the Sun causes this coma to extend outward away from the Sun, forming a huge tail. The tail is complex and consists of two parts. The first part contains the gases released from the comet forming an ion tail that gets elongated in a direction pointing directly away from the Sun and may extend along magnetic field lines for more than 1 astronomical unit (9,321,000 miles; 150,000,000 km). The second part is the coma, or thin atmosphere from which the tail extends, which may become larger than the Sun. Dust released by the comet forms a tail with a slightly different orientation, forming a curved trail that follows the orbital path of the comet around the Sun.

Short-period comets originate in the Kuiper belt, whereas long-period comets originate in the Oort Cloud. Many comets are pulled out of their orbits by gravitational interactions with the Sun and planets or by collisions with other bodies. When these events place comets in orbital paths that cross the inner solar system, these comets may make close orbits to the Sun, and may also collide with planets, including the Earth.

Several space missions have recently investigated the properties of comets. These include Deep Space 1, which flew by Comet Borrelly in 2001. Comet Borrelly is a relative small comet, about 5 miles (8 km) at its longest point, and the mission showed that the comet consists of asteroid-like rocky material, along with icy plains from which the dust jets that form the coma were being emitted. In 1999 the National Aeronautics and Space Administration (NASA) launched the Stardust Comet Sample Return Mission, which flew through the tail of comet Wild 2 and collected samples of the tail in a silica gel and returned them to Earth in 2006. Scientists were expecting to find many particles of interstellar dust, or the extrasolar material that composes the solar nebula, but instead found little of this material; instead they found predominantly silicate mineral grains of Earthlike solar system composition. The samples collected revealed that comet Wild 2 is made of a bizarre mixture of material that includes some particles that formed at the highest temperatures in the early solar system, and some particles that formed at the coldest temperatures. To explain this, scientists have suggested that the rocky material that makes up the comet formed in the inner solar system during its early history, then was ejected to the outer bounds of the solar system beyond the orbit of Neptune, where the icy material was accreted to the comet. Calcium-aluminum inclusions, which represent some of the oldest, highest temperature parts of the early solar system, were also collected from the comet. One of the biggest surprises was the capture of a new class of organic material from the comet tail. These organic molecules are more primitive than any on Earth and than those found in any meteorites; they are known as polycyclic aromatic hydrocarbons. Some samples even contain alcohol. These types of hydrocarbons, thought to exist in interstellar space, may yield clues about the origin of water, oxygen, carbon, and even life on Earth.

Hale-Bopp comet over Billings, Montana, 1997 *(AP images)*

COMETS AND THE ORIGINS OF LIFE

Comets are rich in water, carbon, nitrogen, and complex organic molecules that originate deep in space from radiation-induced chemical processes. Many of the organic molecules in the coma of comets originated in the dust of the solar nebula at the time and location where the comets initially formed in the early history of the solar system. Comets are relatively small bodies that have preserved these early organic molecules in a cold, relatively pristine state. This has led many scientists to speculate that life may have come to Earth on a comet, early in the history of the planet. Clearly, comets both delivered organic material to the early Earth and also destroyed and altered organic material with the heat and shock from impacts. Numerical models of the impact of organic-rich comets with Earth show that some of the organic molecules could have survived the force of impact. The organic molecules in comets may be the source of the prebiotic molecules that led to the origins of life on Earth.

Studies of the chemistry and origin of the atmosphere and oceans suggest that the entire atmosphere, ocean, and much of the carbon on Earth, including that caught up in carbonate rocks like limestone, originated from cometary impact. The period of late impacts of comets and meteorites on Earth lasted about a billion years after the formation of Earth, before greatly diminishing in intensity. Life on Earth began during this time, hinting at a possible link between the transport of organic molecules to Earth by comets, and the development of these molecules into life. The early atmosphere of Earth was also carbon dioxide–rich (much of which came from comets), however, and organic synthesis was also occurring on Earth.

In addition to bringing organic molecules to Earth, the energy from impacts certainly destroyed much of any biosphere that attempted to establish itself on the early Earth. Even the late, very minor K-T impact at Chicxulub had major repercussions for life on Earth. Certainly the early bombardment characterized by many very large impacts would have had a more profound effect on life. Any life that had established itself on Earth would need to be sheltered from the harsh surface environment, perhaps finding refuge along the deep sea volcanic systems known as black smokers, where temperatures remained hot but stable, and nutrients in the form of sulfide compounds were used by early organisms for energy.

EXAMPLE OF A COMETARY IMPACT WITH EARTH

On June 30, 1908, a huge explosion rocked a remote area of central Siberia centered near the Podkamennaya (Lower Stony) Tunguska River, in an area now known as Krasnoyarsk Krai in Russia. After years of study and debate many geologists and other scientists think that this huge explosion was produced by a fragment of Comet Encke that broke off the main body and exploded in the air about five miles (eight km) above the Siberian plains.

The early morning of June 30, 1908, witnessed a huge, pipelike fireball moving across the skies of Siberia, until at 7:17 A.M. a tremendous explosion rocked the Tunguska area and devastated more than 1,160 square miles (3,000 km^2) of forest. The force of the blast is estimated to have been equal to 10–30 megatons (0.91–27 megatonnes), and is thought to have been produced by the explosion, six miles (10 km) above the surface of Earth, of an asteroid or comet with a diameter of 200 feet (60 m). The energy equivalence of this explosion was close to 2,000 times the energy released during the explosion of the Hiroshima atomic bomb. More energy was released in the air blast than the impact and solid earthquakes, demonstrating that the Tunguska impacting body exploded in the air. The pattern of destruction reflects the dominance of atmospheric shock waves rather than solid earthquakes that are estimated to have been about a magnitude 5 earthquake. Atmospheric shock waves were felt thousands of miles away, and people located closer than 60 miles (100 km) from the site of the explosion were knocked unconscious; some were thrown into the air by the force of the explosion. Fiery clouds and deafening explosions were heard more than 600 miles (965 km) from Tunguska.

For a long time one of the biggest puzzles at Tunguska was the absence of an impact crater, despite all other evidence that points to an impact origin for this event. Many scientists now think that a piece of a comet, Comet Encke, broke off the main body as it was orbiting nearby Earth, and this fragment entered Earth's atmosphere and exploded about 5–6 miles (8–10 km) above the Siberian plains at Tunguska. This model was pioneered by Slovak astronomer Lubor Kresak, following earlier suggestions by the British astronomer F. J. W. Whipple in the 1930s that the bolide (a name for any unidentified object entering the planet's atmosphere) at Tunguska may have been a comet. Other scientists suggest the bolide may have been a meteorite, since comets are weaker than metallic or stony meteorites, and more easily break up and explode in the atmosphere before they hit Earth's surface. If the Tunguska bolide was a comet, it would likely have broken up higher in the atmosphere. In either case calculations show that, because of Earth's rotation, if the impact explosion happened only four hours and 47 minutes later, the city of Saint Petersburg would have been completely destroyed by the air blast. Air blasts from disintegrating meteorites or comets the size of the Tunguska explosion occur about once every 300 years on Earth, whereas smaller explosions, about the size of the nuclear bombs dropped on Japan, occur in the upper atmosphere about once per year.

All the trees in the Siberian forest in an area the size of a large city were leveled by the explosion of Tunguska, which fortunately was unpopulated at the time. But a thousand reindeer belonging to the Evenki people of the area were reportedly killed by the blast. The pattern of downed trees indicates that the projectile traveled from the southeast to the northwest as it exploded. The height of the explosion over Tunguska is about the optimal height for an explosion-induced air burst to cause maximum damage to urban areas, and calculations suggest that if the area was heavily populated at the time of the impact, at least 500,000 people would have died. Despite the magnitude and significance of this event, the Tunguska region was very remote, and no scientific expeditions to the area to investigate the explosion were mounted until 1921, 13 years after the impact, and even then the first expedition reached only the fringes of the affected area. The first scientific expedition was led by geologist Leonid Kulik, who was looking for meteorites along the Podkamennaya Tunguska River basin, and he heard stories from the local people of the giant explosion that happened in 1908, and that the explosion had knocked down trees, blown roofs off huts, and knocked people over and even caused some to become deaf from the noise. Kulik then convinced the Russian government that an expedition needed to be mounted into the remote core of the Tunguska blast area, and this expedition reached the core of the blast zone in 1927. Kulik and his team found huge tracts of flattened and burned trees, but they were unable to locate an impact crater.

In June 2007 a team of scientists from the University of Bologna suggested that the small Lake Cheko, located about 5 miles (8 km) from the epicenter of the blast, may be the impact site. Other scientists challenge this interpretation, noting that the lake has thick sediments, implying an older age than the age of the impact.

The atmospheric blast from the Tunguska explosion raced around the planet two times before diminishing. Residents of Siberia who lived within about 50 miles (80 km) of the blast site reported unusual glowing light from the sky for several weeks after the explosion. It is possible that this light was being reflected by a stream of dust particles that were ripped off a comet as it entered the atmosphere before colliding with Earth's surface. The unusual nighttime illumination was reported from across Europe and western Russia, showing the extent of the dust stream in the atmosphere.

As the fireball from the Tunguska airburst moved through the atmosphere, the temperatures at the center of the fireball were exceedingly hot, estimated to be 30 million degrees Fahrenheit (16.6 million Celsius). On the ground trees were burned and scorched, and silverware utensils in storage huts near the center of the blast zone were melted by the heat. After the impact leveled the trees for a distance of about 25 miles (40 km) around the center of the impact, forest fires ravaged the area, but typically burned only the outer surface of many trees, as if the fires were a short-lived flash of searing heat.

The type of body that exploded above Tunguska has been the focus of much speculation and investigation. One of the leading ideas is that the impact was caused by a comet that exploded in the atmosphere above Tunguska, a theory pioneered by F. J. W. Whipple in a series of papers from 1930 to 1934. In the 1960s small silica and magnetite spherules that represent melts from an extraterrestrial source were found in soil samples from Tunguska, confirming that a comet or meteorite had exploded above the site. Further analysis of the records of the airblast indicated that several pressure waves were recorded by the event. The first was the type associated with the rapid penetration of an object into the atmosphere, and at least three succeeding bursts recorded the explosions of a probably fragmented comet about five miles (eight km) above the surface.

There have been other reported explosions, or possible explosions, of meteorites above the surface of Earth, creating air blasts since the Tunguska event, although none has been as spectacular. On August 13, 1930, a body estimated to be about 10 percent the size of the Tunguska bolide exploded above the Curuca River in the Amazonas area in Brazil, but documentation of this event is poor. On May 31, 1965, an explosion with the force equivalent of 600 tons (544 tonnes) of TNT was released eight miles (13 km) above southeastern Canada, and approximately 0.4 ounce (1 g) of meteorite material was recovered from this event. Similar sized events, also thought to be from meteorite explosions at about eight miles (13 km) above the surface, were reported from southeast Canada on May 31, 1965, over Lake Huron (Michigan) on September 17, 1966, and over Alberta, Canada, on February 5, 1967. No meteorite material was recovered from any of these events. Two mysterious explosions, probably meteorites exploding, with an equivalent of about 25 tons (23 tonnes) of TNT, were reported, strangely, over the same area of Sassowo, Russia, on April 12, 1992, and July 8, 1992. A larger explosion and airburst, estimated to be equivalent to 10,000 tons of TNT, was reported over Lugo, Italy, on January 19, 1993, and another 25-ton (23-tonne) event over Cando, Spain, on January 18, 1994. Russia was struck again, this time in the Bodaybo region, by a 500–5,000 ton (450–4,500 tonne) equivalent blast on September 25, 2002, after a 26,000-ton (23,600-tonne) airburst from a meteorite explosion was recorded over the Mediterranean between Greece and Libya. The last reported airburst was from a high-altitude explosion, 27 miles (43 km) over Snohomish, Washington, on June 3, 2004. Clearly airbursts associated with the explosion of meteorites or comets are fairly common events, just as events as strong as the Tunguska explosion happen only about once every 300 years.

See also ASTEROID; ASTRONOMY; ASTROPHYSICS; ORIGIN AND EVOLUTION OF THE EARTH AND SOLAR SYSTEM; SOLAR SYSTEM.

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constellation Human groupings of stars in the sky into patterns, even though they may be far apart and lined up only visibly, are known as constellations. About 6,000 stars (and other points of light such as distant galaxies, planetary nebulas, quasars, etc.) are visible to the naked eye from Earth, and an irresistible tendency to see patterns and figures in these points of light has persisted for generations going back thousands of years. Peoples of many cultures have grouped these apparent configurations of points of light in the sky into patterns called constellations, the most famous of which are named after ancient Greek mythological beings. Typically most stars that make up a constellation physically exist far apart in space, and appear grouped near to one another only when viewed from Earth. Some of the earliest records of constellations date back to about 2500 B.C.E., from the Mesopotamian region, where early peoples used the patterns in the stars to help tell stories, mixing mythology, religion, cultural values, and tradition from generation to generation. There are some references to patterns of stars being grouped into constellations by the ancient Chinese and Jewish cultures that may go back to 4000 B.C.E. The peoples and stories changed with each generation, but the constellations were always there to remind the new generations that their elders were watching from above. Some cultures also used constellations for navigation and for marking the seasons. For instance, the star Polaris, which is part of the Little Dipper, indicates the north direction,

THE CONSTELLATIONS

Name/Meaning (Latin [English])	Genitive Form of Latin Name	Abbreviation	Approximate Position (Equatorial Coordinates)	
			RA(h)	δ(°)
Andromeda (name: princess)	Andromedae	And	1	+40
Aquarius (water bearer)	Aquarii	Aqr	23	-15
Aquila (eagle)	Aquilae	Aql	20	+5
Ara (altar)	Arae	Ara	17	-55
Argo Navis (ship of Argonauts), now split into the modern constellations: Carina, puppies, Pyxis, and Vela				
Aries (ram)	Arietis	Ari	3	+20
Auriga (charioteer)	Aurigae	Aur	6	+40
Boötes (berdsman)	Boötis	Boo	15	+30
Cancer (crab)	Cancri	Cnc	9	+20
Canis Major (great dog)	Canis Majoris	CMa	7	-20
Canis Minor (little dog)	Canis Minoris	CMi	8	+5
Capricornus (sea goat)	Capricorni	Cap	21	-20
Cassiopeia (name: queen)	Cassiopeiae	Cas	1	+60
Centaurus (centaur)	Centauri	Cen	13	-50
Cepheus (name: king)	Cephei	Cep	22	+70
Cetus (whale)	Ceti	Cet	2	-10
Corona Austrina (southern crown)	Coronae Australis	CrA	19	-40
Corona Borealis (northern crown)	Coronae Borealis	CrB	16	+30
Corvus (crow)	Corvi	Crv	12	-20
Crater (cup)	Crateris	Crt	11	-15
Cygnus (swan)	Cygni	Cyg	21	+40
Delphinus (dolphin)	Delphini	Del	21	+10
Draco (dragon)	Draconis	Dra	17	+65

and, with its fairly constant position in the sky, has served as a navigational aid for ages. Some cultures have used the first appearance of certain stars or constellations just above the horizon at daybreak to mark the start of different seasons, such as the harvest, spring, and end of winter. In other cases the relative positions of different constellations were used by some mythological cultures to form predictions of a person's destiny, thus creating the field of astrology.

Greek astronomers later adopted many of the ancient Mesopotamian constellations, to which they added their own culture and stories, establishing a now commonly used set of 48 constellations (see the table the Constellations). These were first codified by Eudoxus of Cnidus, then Hipparchus, and finally

Name/Meaning (Latin [English])	Genitive Form of Latin Name	Abbreviation	Approximate Position (Equatorial Coordinates)	
			RA(h)	δ(°)
Equuleus (little horse)	Equulei	Equ	21	+10
Eridanus (name: river)	Eridani	Eri	3	-20
Gemini (twins)	Geminorum	Gem	7	+20
Hercules (name: hero)	Herculis	Her	17	+30
Hydra (sea serpent; monster)	Hydrae	Hya	10	-20
Leo (lion)	Leonis	Leo	11	+15
Lepus (hare)	Leporis	Lep	6	-20
Libra (scale; balance beam)	Librae	Lib	15	-15
Lupus (wolf)	Lupi	Lup	15	-45
Lyra (lyre)	Lyrae	Lyr	19	+40
Ophiuchus (serpent bearer)	Ophiuchii	Oph	17	0
Orion (name: great hunter)	Orionis	Ori	5	0
Pegasus (name : winged horse)	Pegasi	Peg	22	+20
Perseus (name: hero)	Persei	Per	3	+45
Pisces (fishes)	Piscium	Psc	1	+15
Piscis Austrinus (southern fish)	Piscis Austrini	PsA	22	-30
Sagitta (arrow)	Sagittae	Sge	20	+10
Sagittarius (archer)	Sagittarii	Sgr	19	-25
Scorpius (scorpion)	Scorpii	Sco	17	-40
Serpens (serpent)	Serpentis	Ser	17	0
Taurus (bull)	Tauri	Tau	4	+15
Triangulum (triangle)	Trianguli	Tri	2	+30
Ursa major (great bear)	Ursae Majoris	UMa	11	+50
Ursa Minor (little bear)	Ursae Minoria	UMi	15	+70
Virgo (virgin; maiden)	Virginis	Vir	13	0

THE MODERN CONSTELLATIONS

Name/Meaning (Latin [English])	Genitive Form of Latin Name	Abbreviation	Approximate Position (Equatorial Coordinates)	
			RA(h)	δ(°)
Antlia (air pump)	Antiae	Ant	10	-35
Apus (bird of paradise)	Apodis	Aps	16	-75
Caelum (sculptor's chisel)	Caeli	Cae	5	-40
Camelopardalis (giraffe)	Camelopardalis	Cam	6	+70
Canes Venatici (hunting dogs)	Canum Venaticorum	CVn	13	+40
Carina (keel)*	Carinae	Car	9	-60
Chamaeleon (chameleon)	Chamaeleontis	Cha	11	-80
Circinus (compasses)	Circini	Cir	15	-60
Columba (dove)	Columbae	Col	6	-35
Coma Berenices (Berenice's hair)	Comae Berenices	Com	13	+20
Crux (southern cross)	Crucis	Cru	12	-60
Dorado (swordfish)	Doradus	Dor	5	-65
Fornax (furnace)	Fornacis	For	3	-30
Grus (crane)	Gruis	Gru	22	-45
Horologium (clock)	Horologii	Hor	3	-60
Hydrus (water snake)	Hydri	Hyi	2	-75
Indus (Indian)	Indi	Ind	21	-55
Lacerta (Lizard)	Lacertae	Lac	22	+45
Leo Minor (little lion)	Leonis Minoris	LMi	10	+35
Lynx (lynx)	Lyncis	Lyn	8	+45
Mensa (table mountain)	Mensae	Men	5	-80
Microscopium (microscope)	Microscopii	Mic	21	-35
Monoceros (unicorn)	Monocerotis	Mon	7	-5
Musca (fly)	Muscae	Mus	12	-70
Norma (carpenter's square)	Normae	Nor	16	-50
Octans (octant; navigation device)	Octantis	Oct	22	-85
Pavo (peacock)	Pavonis	Pav	20	-65
Phoenix (Phoenix; mythical bird)	Phoenicis	Phe	1	-50
Pictor (painter's easel)	Pictoris	Pic	6	-55
Puppis (stern)*	Puppis	Pup	8	-40
Pyxis (nautical compass)*	Pyxidis	Pyx	9	-30

Name/Meaning (Latin [English])	Genitive Form of Latin Name	Abbreviation	Approximate Position (Equatorial Coordinates)	
			RA(h)	δ(°)
Reticulum (net)	Reticuli	Ret	4	-60
Sculptor (sculptor's workshop	Sculptoris	Scl	0	-30
Scutum (shield)	Scuti	Sct	19	-10
Sextans (sextant)	Sextantis	Sex	10	0
Telescopium (telescope)	Telescopii	Tel	19	-50
Triangulum Australe (southern triangle)	Trianguli Australe	TrA	16	-65
Tucana (toucan)	Tucanae	Tuc	0	-65
Vela (sail)*	Velorum	Vel	9	-50
Volans (flying fish)	Volantis	Vol	8	-70
Vulpecula (fox)	Vulpeculae	Vul	20	+25

*Originally part of ancient constellation Argo Navis (ship of Argonauts)

compiled in the work Syntaxis by Ptolemy about 150 B.C.E.

As the Roman Empire expounded, the Romans adopted the Greek constellations and spread their usage throughout the Western world. But, as the Roman Empire declined and the Dark Ages ensued, the light of the constellations was largely preserved only in the Arabic world, where the works were translated into *The Almagest,* in which many of the older observations were embellished and more detailed observations added. At the end of the Dark Ages the traditional Greek constellations experienced a revival in Europe during the Renaissance, initiating a period of rapid scientific inquiry. In 1603 the German astronomer Johann Bayer published *Uranometria,* the first major star catalog covering the entire celestial sphere visible from Earth. Bayer introduced the nomenclature of using Greek letters for the main stars in each constellation, assigning α (alpha) to the brightest, β (beta) to the second brightest, and so on, as well as named a dozen new constellations in the Southern Hemisphere. Since then other astronomers have named additional constellations, including several named by the Polish-German astronomer Johannes Hevelius, and the 18th-century French astronomer Nicolas-Louis de Lacaille. Astonomers today recognize 88 different constellations, including 47 of the 48 original Greek constellations. These are listed in the table the Modern Constellations.

See also ASTRONOMY; GALAXIES; GALAXY CLUSTERS; UNIVERSE.

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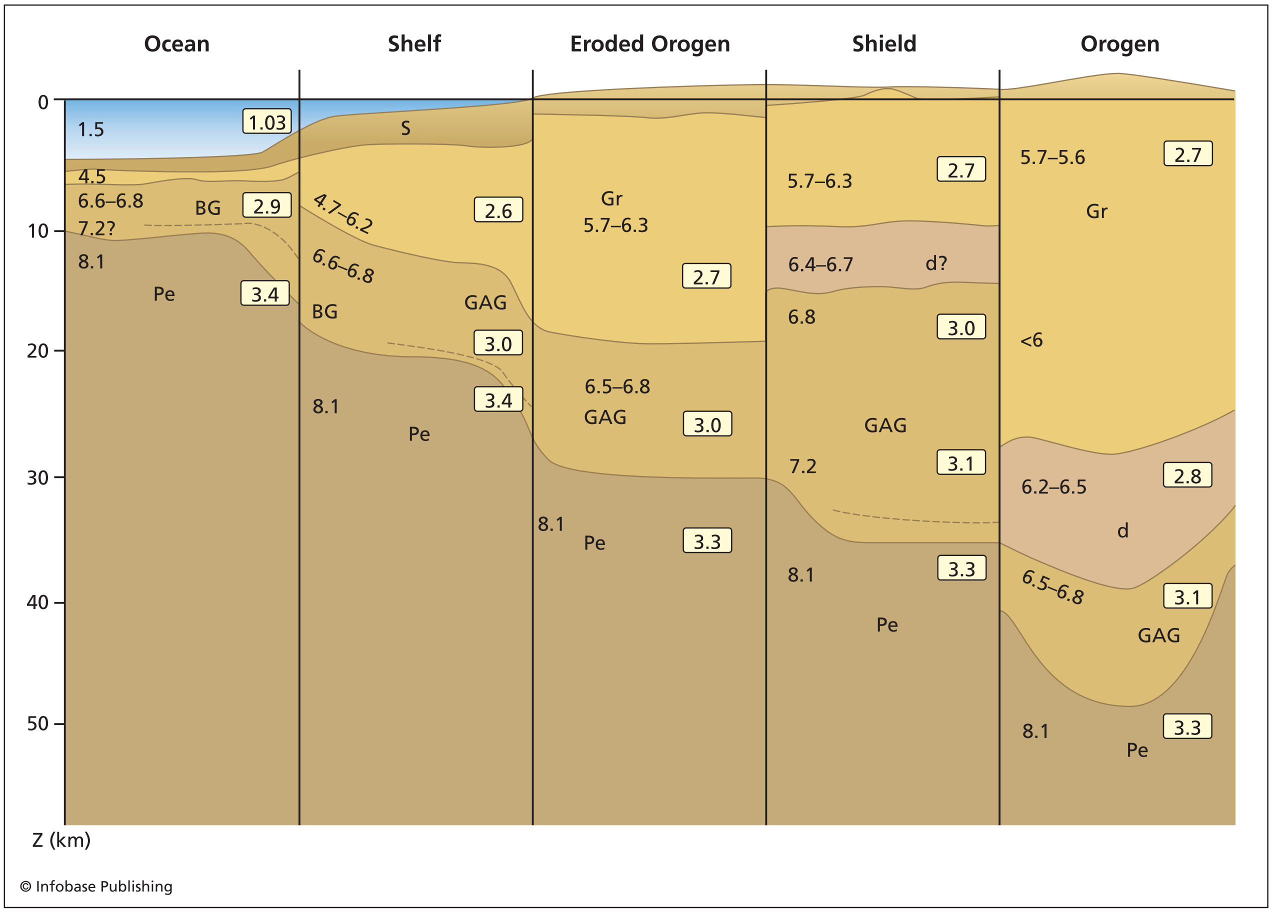
continental crust Continental crust covers about 34.7 percent of the Earth's surface, whereas exposed continents cover only 29.22 percent of the surface, with the discrepancy accounted for in the portions of continents that lie underwater on the continental shelves. Its lateral boundaries are defined by the slope break between continental shelves and slopes, and its vertical extent is defined by a jump in seismic velocities to 4.7–5 miles per second (7.6–8.0 km/s) at the Mohorovicic discontinuity. The continental crust ranges in thickness from about 12.5 to about 37 miles (20–60 km), with an average thickness of 24 miles (39 km). The continents are divided into orogens, made of linear belts of concentrated deformation, and cratons, marking the stable, typically older interiors of the continents. The distribution of elevation of continents and oceans can be portrayed on a curve showing the percentage of land at a specific elevation, versus elevation, known as the hypsometric curve, or the hypsographic curve. The curve is a cumulative frequency profile representing the statistical distribution of areas of the Earth's solid surface above or below mean sea level. The hypsometric curve is strongly bimodal, reflecting the two-tier distribution of land in continents close to sea level, and on ocean floor abyssal plains 1.9–2.5 miles (3–4 km) below sea level. Relatively little land surface is found in high mountains or in deep-sea trenches.

Most of the continental crust is now preserved in Archean cratons that form the cores of many continents. They are composed of ancient rocks that have been stable for billions of years, since the Archean. Cratons generally have low heat flow, few if any earthquakes, and no volcanism, and many are overlain by flat-lying shallow water sedimentary sequences. Continental shields are places where the cratonic crust is exposed at the surface, whereas continental platforms are places where the cratonic rocks are overlain by shallow-water sedimentary rocks, presently exposed at the surface.

Most cratons have a thick mantle root or tectosphere, characterized seismologically and from xenolith studies to be cold and refractory, having had basaltic melt extracted from it during the Archean. Seismological studies have shown that many parts of the tectosphere are strongly deformed, with most of the minerals oriented in planar or linear fabrics. Current understanding about the origin of stable continental cratons and their roots hinges on recognizing which processes change the volume and composition of continental lithosphere with time, and how and when juvenile crust evolved into stable continental crust. Despite decades of study, several major unresolved questions remain concerning Archean tectosphere: How is it formed? Large quantities of melt extraction (ultramafic in composition, if melting occurred in a single event) are required from petrological observations, yet little of this melt is preserved in Archean cratons, which are character-



General crustal structure of different provinces as determined by seismology. Numbers in boxes represent densities in grams/cm^3, and other numbers represent the seismic velocity of P waves in kilometers per second: BG = basalt-gabbro, GAG = amphibolite and granulite, Pe = peridotite, d = diorite, An Ga = anorthositic gabbro, S = sediments, Gr = granitic-gneiss upper crust, M = Mohorovicic discontinuity.

ized by highly evolved crust compositions. In what tectonic settings is it formed? Hypotheses range from intraplate, plume-generated settings to convergent margin environments. Finally, once formed, does the chemical buoyancy and inferred rheological strength of the tectosphere preserve it from disruption? Until recently most scientists would argue that cratonic roots last forever—isotopic investigations of mantle xenoliths from the Kaapvaal, Siberian, Tanzanian, and Slave cratons document the longevity of the tectosphere in these regions. However, the roots of some cratons are now known to have been lost, including the North China craton, and the processes of the loss of the tectosphere are as enigmatic as the processes that form the roots.

Orogens and orogenic belts are elongate regions that are eroded mountain ranges, and typically have abundant folds and faults. Young orogens are mountainous and include such familiar mountain ranges as the Rockies, Alps, and the slightly older Appalachians. Many Archean cratons are welded together by Proterozoic and younger orogens. In fact many Archean cratons can be divided into smaller belts that represent fragments of the planet's oldest orogenic belts.

Orogens have been added to the edges of the continental shield and cratons through processes of mountain building related to plate tectonics. Mountain belts are of three basic types, including fold and thrust belts, volcanic mountain ranges, and fault-block ranges. Fold and thrust belts are contractional mountain belts, formed where two tectonic plates collided, forming great thrust faults, folds, metamorphic rocks, and volcanic rocks. Detailed mapping of the structure in the belts can enable geologists to reconstruct their history and essentially pull them back apart. Investigations have revealed that many of the rocks in fold- and thrust-belt types of mountain ranges were deposited on the bottom of the ocean, continental rises, slope, shelves, or on ocean margin deltas. When the two plates collide, many of the sediments get scraped off and deformed, forming the mountain belts. Thus fold and thrust mountain belts mark places where oceans have closed.

Volcanic mountain ranges include Japan's Fuji and Mount St. Helens in the Cascades of the western United States. These mountain ranges are not formed primarily by deformation, but by volcanism associated with subduction and plate tectonics.

Fault-block mountains, such as the Basin and Range Province of the western United States, are formed by the extension or pulling apart of the continental crust, forming elongate valleys separated by tilted fault-bounded mountain ranges.

Every rock type known on Earth is found on the continents, so averaging techniques must be used to determine the overall composition of the crust. Estimates suggest that continental crust has a composition equivalent to andesite (or granodiorite) and is enriched in incompatible trace elements, the elements that do not easily fit into lattices of most minerals and tend to get concentrated in magmas.

The continents exhibit a broadly layered seismic structure that is different from place to place, and different in orogens, cratons, and parts of the crust with different ages. In shields the upper layer may typically be made of a few hundred meters of sedimentary rocks underlain by generally granitic types of material with seismic velocities of 3.5 to 3.9 miles per second (5.7–6.3 km/s) to depths of a couple to 6 miles (a few to 10 km), then a layer with seismic velocities of 3.9–4.2 miles per second (6.4–6.7 km/s). The lower crust is thought to be made of layered amphibolite and granulite with velocities of 4.2–4.5 miles per second (6.8–7.2 km/s). Orogens tend to have thicker, low-velocity upper layers and a lower-velocity lower crust.

Considerable debate and uncertainty surrounds the timing and processes responsible for the growth of the continental crust from the mantle. Most scientists agree that most of the growth occurred early in Earth history, since more than half of the continental crust is Archean in age, and about 80 percent is Precambrian. Some debate centers on whether early tectonic processes resembled those currently operating, or whether they differed considerably. The amount of current growth and how much crust is being recycled back into the mantle are currently poorly constrained. Most petrological models for the origin of the crust require that it be derived by a process including partial melting from the mantle, but simple mantle melting produces melts that are not as chemically evolved as the crust. Therefore the crust is probably derived through a multistage process, most likely including early melts derived from seafloor spreading and island arc magmatism, with later melts derived during collision of the arcs with other arcs and continents. Other models seek to explain the difference by calling on early higher temperatures leading to more evolved melts.

See also CRATON; GREENSTONE BELTS; OROGENY.

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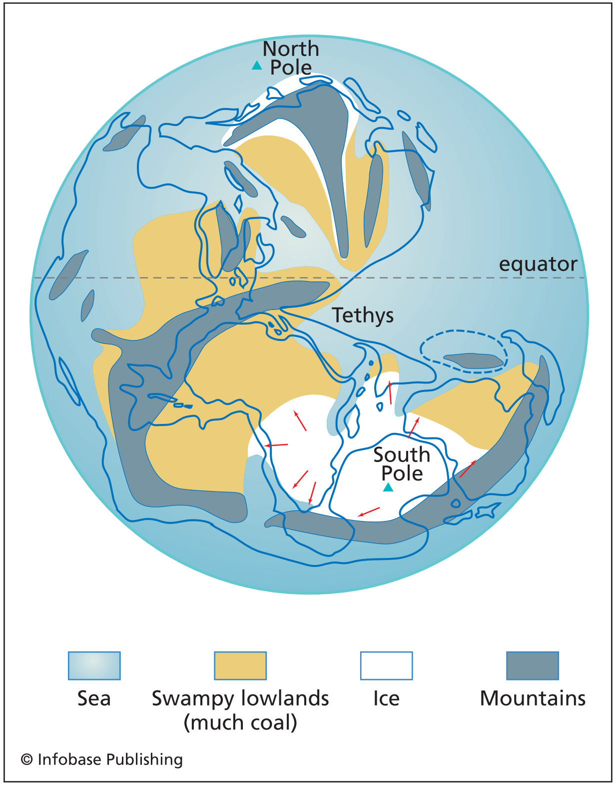
continental drift The theory of continental drift was a precursor to plate tectonics. Proposed most clearly by Alfred Wegener in 1912, continental drift states that the continents are relatively light objects that are floating and moving freely across a substratum of oceanic crust. The theory was largely discredited because it lacked a driving mechanism, and seemed implausible if not physically impossible to most geologists and geophysicists at the time. But many of the ideas of continental drift were later incorporated into the paradigm of plate tectonics.

Early geologists recognized many of the major tectonic features of the continents and oceans. Cratons are very old, stable portions of the continents that have been inactive since the Precambrian. They typically exhibit subdued topography, including gentle arches and basins. Orogenic belts are long, narrow belts of structurally disrupted and metamorphosed rocks, typified (when active) by volcanoes, earthquakes, and folding of strata. Abyssal plains are stable, flat parts of the deep oceanic floor, whereas oceanic ridges are mountain ranges beneath the sea with active volcanoes, earthquakes, and high heat flow. To explain the large-scale tectonic features of the Earth, early geologists proposed many hypotheses, including popular ideas that the Earth was either expanding or shrinking, forming ocean basins and mountain ranges. In 1910–25 Wegener published a series of works including his 1912 treatise on *The Origin of Continents and Oceans*. Wegener proposed that the continents were drifting about the surface of the planet, and that they once fit back together to form one great supercontinent, Pangaea. To fit the coastlines of the different continental masses together to form his reconstruction of Pangaea, Wegener defined the continent/ocean transition as the outer edge of the continental shelves. The continental reconstruction proposed by Wegener showed remarkably good fits between coastlines on opposing sides of ocean basins, such as the Brazilian Highlands of South America fitting into the Niger delta region of Africa. Wegener was a meteorologist, and since he was not formally trained as a geologist, few scientists at the time believed his findings, although we now know that he was largely correct.

Most continental areas lie approximately 985 feet (300 m) above sea level, and if we extrapolate present erosion rates back in time, we find that continents would be eroded to sea level in 10–15 million years. This observation led to the application of the principle of isostasy to explain the elevation of the continents. Isostasy, which is essentially Archimedes' principle, states that continents and high topography are buoyed up by thick continental roots floating in a denser mantle, much like icebergs floating in water. The principle of isostasy states that the elevation of any large segment of crust is directly proportional to the thickness of the crust. It is significant that geologists working in Scandinavia noticed that areas that had recently been glaciated were rising quickly relative to sea level, and they equated this observation with the principle of isostatic rebound. The flow of mantle material within the zone of low viscosity beneath the continental crust accommodates isostatic rebound to compensate for the rising topography. These observations revealed that mantle material can flow at rates of a couple of inches (several centimeters) per year.

In *The Origin of Continents and Oceans* Wegener fit all the continents back together to form a Permian supercontinent, Pangaea (or "all land"). Wegener also used indicators of past climates, such as locations of ancient deserts and glacial ice sheets, and distributions of certain plant and animal species to support his ideas. Wegener's ideas found support from a famous South African geologist, Alex L. Du Toit, who in 1921 matched the stratigraphy and structure across the Pangaea landmass. Du Toit found the same plants, such as the Glossopterous fauna, across Africa and South America. He also documented similar reptiles and even earthworms across narrow belts of Wegener's Pangaea, supporting the concept of continental drift.



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Modification of Alfred Wegener's reconstruction of Pangaea, originally from *Origin of Continents and Oceans*

Even with evidence such as the matching of geological belts across Pangaea, most geologists and geophysicists doubted the idea due to the lack of a conceivable driving mechanism, thinking it mechanically impossible for relatively soft continental crust to plow through the much stronger oceans. Early attempts at finding a mechanism were implausible and included such ideas as tides pushing the continents. Because of the lack of credible driving mechanisms, continental drift encountered stiff resistance from the geologic community, as few could understand how continents could plow through the mantle.

In 1928 British geologist Arthur Holmes suggested a driving mechanism for moving the continents. He proposed that heat produced by radioactive decay caused thermal convection in the mantle, and that the laterally flowing mantle dragged the continents with the convection cells. He reasoned that if the mantle can flow to allow isostatic rebound following glaciation, then maybe it can flow laterally as well. The acceptance of thermal convection as a driving mechanism for continental drift represented the foundation of modern plate tectonics. In the 1950s and 1960s the paleomagnetic data were collected from many continents and argued strongly that the continents had indeed been shifting, both with respect to the magnetic pole and also with respect to one another. When seafloor spreading and subduction of oceanic crust beneath island arcs was recognized in the 1960s, the model of continental drift was modified to become the new plate tectonic paradigm that revolutionized and unified many previously diverse fields of the earth sciences.

See also Du Toit, Alexander; Holmes, Arthur; plate tectonics; supercontinent cycles; Wegener, Alfred.

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continental margin Continental margins are the transition zone between thick, buoyant continental crust and the thin, dense submerged oceanic crust. There are several different types, depending on the tectonic setting. Passive, trailing, or Atlantic-type margins form where an extensional boundary evolves into an ocean basin, and new oceanic crust is added to the center of the basin between continental margins that originally faced one another. These margins were heated and thermally elevated during rifting and gradually cooled and thermally subsided for several tens of millions of years, slowly accumulating thick sequences of relatively flat sediments, forming continental shelves. Continental slopes and rises succeed these shelves seaward. The ocean/continent boundary typically occurs at the shelf/slope break on these Atlantic-type margins, where water depths average fewer than a thousand feet (a couple of hundred meters). Passive margins do not mark plate boundaries but rim most parts of many oceans, including the Atlantic and Indian, and form around most of Antarctica and Australia. Young, immature passive margins are beginning to form along the Red Sea.

Convergent, leading, or Pacific-type margins form at convergent plate boundaries. They are characterized by active deformation, seismicity, and volcanism, and some have thick belts of rocks known as accretionary prisms scraped off of a subducting plate and added to the overriding continental plate. Convergent margins may have a deep sea trench up to seven miles (11 km) deep marking the boundary between the continental and oceanic plates. These trenches form where the oceanic plate is bending and plunging deep into the mantle. Abundant folds and faults in the rocks characterize convergent margins. Other convergent margins are characterized by old eroded bedrock near the margin, exposed by a process of sediment erosion where the edge of the continent is eroded and drawn down into the trench.

A third type of continental margin forms along transform or transcurrent plate boundaries. These are characterized by abundant seismicity and deformation, and volcanism is limited to certain restricted areas. Deformation along transform margins tends to be divided into different types, depending on the orientation of bends in the main plate boundary fault. Constraining bends form where the shape of the boundary restricts motion on the fault, and are characterized by strong folding, faulting, and uplift. The Transverse Ranges of southern California form a good example of a restraining bend. Sedimentary basins and subsidence characterize bends in the opposite direction, where the shape of the fault causes extension in areas where parts of the fault diverge during movement. Volcanic rocks form in some of these basins. The Gulf of California and Salton trough have formed in areas of extension along a transform margin in southern California.

See also convergent plate margin processes; divergent plate margin processes; plate tectonics; transform plate margin processes.

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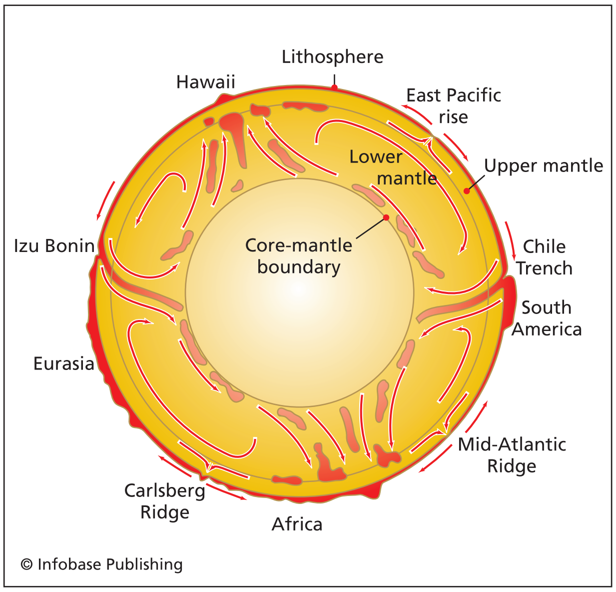
convection and the Earth's mantle The main heat transfer mechanism in the Earth's mantle is convection, a thermally driven process where heating at depth causes material to expand and become less dense, causing it to rise while being replaced by complimentary cool material that sinks. This moves heat from depth to the surface in a very efficient cycle, since the material that rises gives off heat as it rises and cools, and the material that sinks gets heated only to rise again eventually. Convection is the most important mechanism by which the Earth is loosing heat, with other mechanisms including conduction, radiation, and advection. However, many of these mechanisms work together in the plate tectonic cycle. Mantle convection brings heat from deep in the mantle to the surface, where the heat released forms magmas that generate the oceanic crust. The midocean ridge axis is the site of active hydrothermal circulation and heat loss, forming black smoker chimneys and other vents. As the crust and lithosphere move away from the midocean ridges, it cools by conduction, gradually subsiding (according the square root of its age) from about 1.5–2.5 miles (2.5–4.0 km) below sea level. Heat loss by mantle convection is therefore the main driving mechanism of plate tectonics, and the moving plates can be thought of as the conductively cooling boundary layer for large-scale mantle convection systems.

The heat transferred to the surface by convection is produced by decay of radioactive elements, producing isotopes such as uranium 235, thorium, 232, and potassium 40, remnant heat from early heat-producing isotopes such as iodine 129, remnant heat from accretion of the Earth, heat released during core formation, and heat released during impacts of meteorites and asteroids. Early in the history of the planet at least part of the mantle was molten, and the Earth has been cooling by convection ever since. Estimating how much the mantle has cooled with time is difficult, but reasonable estimates suggest that the mantle may have been up to a couple of hundred degrees hotter in the earliest Archean.



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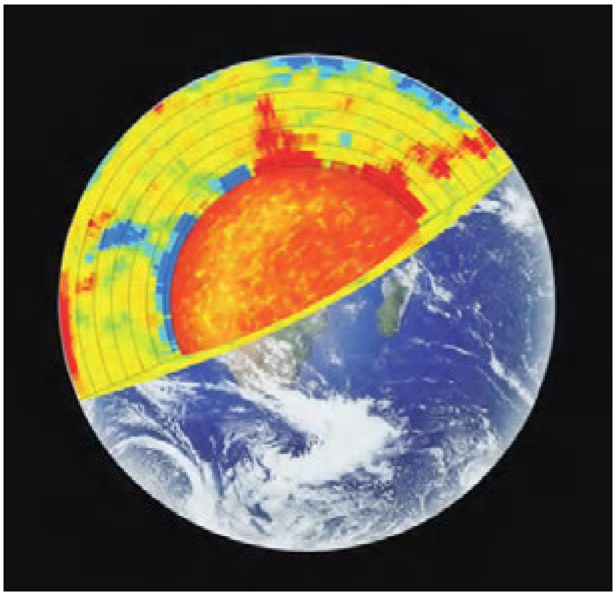
Cross section of Earth showing possible modes of mantle convection

The rate of mantle convection depends on the ability of the material to flow. The resistance to flow is a quantity measured as viscosity, defined as the ratio of shear stress to strain rate. Fluids with high viscosity are more resistant to flow than materials with low viscosity. The present viscosity of the mantle is estimated to be 10^{20}–10^{21} Pascal seconds (Pa/s) in the upper mantle and 10^{21}–10^{23} Pa/s in the lower mantle, values sufficient for allowing the mantle to convect, and complete an overturn cycle once every 100 million years. The viscosity of the mantle is temperature dependent, so the mantle may have been able to flow and convectively overturn much more quickly in early Earth history, making convection an even more efficient process and speeding the rate of plate tectonic processes.

Current ongoing debate and research concerns the style of mantle convection in the Earth. The upper mantle is relatively heterogeneous and extends to a depth of 416 miles (670 km), where there is a pronounced increase in seismic velocities. The lower mantle is more homogeneous, and extends to a region known as D″ (pronounced dee-double-prime) at 1,678 miles (2,700 km), marking the transition into the liquid outer core. One school of mantle convection thought suggests that the entire mantle, including both the upper and lower parts, convects as one unit. Another school of thought posits that the mantle convection consists of two layers, with the lower mantle convecting separately from the upper mantle. A variety of these models, presently held by the majority of geophysicists, holds that there is two-layer convection, but that subducting slabs are able to penetrate the 670-kilometer discontinuity from above, and that mantle plumes that rise from the D″ region can penetrate the 670-kilometer discontinuity from below.

The shapes that mantle convection cells take include many possible forms that are reflected to a first order by the distribution of subduction zones and midocean ridge systems. The subduction zones mark regions of downwelling, whereas the ridge system marks broad regions of upwelling. Material is upwelling in a broad planiform cell beneath the Atlantic and Indian Oceans, and downwelling in the circum-Pacific subduction zones. There is thought to be a large plumelike "superswell" beneath part



Real data on a cutaway of Earth showing movement of deep slabs of rock in mantle. Sinking slabs are blue, mantle is yellow, and rising molten rock is red. The sinking slabs, including one (at upper left) descending from the Caribbean, are up to 930 miles (1,500 km) across and penetrate up to 1,800 miles (2,900 km) to the D″ region at the core-mantle boundary. The deep slabs can be detected by measuring the arrival times at points around the world of seismic shear waves produced by earthquakes. These waves travel faster through dense, cool rock than warm rock. *(Steve Grand, Texas University/Photo Researchers, Inc.)*

of the Pacific that feeds the planiform East Pacific rise. Mantle plumes that come from the deep mantle punctuate this broad pattern of upper-mantle convection, and their plume tails must be distorted by flow in the convecting upper mantle.

The pattern of mantle convection deep in geological time is uncertain. Some periods such as the Cretaceous seem to have had much more rigorous mantle convection and surface volcanism. More or different types or rates of mantle convection may have helped to allow the early Earth to lose heat more efficiently. Some computer models allow periods of convection dominated by plumes, and others dominated by overturning planar cells similar to the present Earth. Some models suggest cyclic relationships, with slabs pooling at the 670-kilometer discontinuity, then suddenly all sinking into the lower mantle, causing a huge mantle overturn event. Further research is needed on linking the preserved record of mantle convection in the deformed continents to help interpret the past history of convection.

See also BLACK SMOKER CHIMNEYS; DIVERGENT PLATE MARGIN PROCESSES; PLATE TECTONICS.

FURTHER READING

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convergent plate margin processes Structural, igneous, metamorphic, and sedimentological processes that occur in the region affected by forces associated with the convergence of two or more plates are grouped under the heading of convergent plate margin processes. Convergent plate boundaries are of two fundamental types, subduction zones and collision zones. Subduction zones are in turn of two basic types, the first of which is found where oceanic lithosphere of one plate descends beneath another oceanic plate, such as in the Philippines and Marianas of the southwest Pacific. The second type of subduction zone forms where an oceanic plate descends beneath a continental upper plate, such as in the Andes of South America. The southern Alaska convergent margin is particularly interesting, as it records a transition from an ocean/continent convergent boundary to an ocean/ocean convergent boundary in the Aleutians.

Arcs have several different geomorphic zones defined largely on their topographic and structural expressions. The active arc is the topographic high with volcanoes, and the backarc region stretches from the active arc away from the trench, and it may end in an older rifted arc or continent. The forearc basin is a generally flat topographic basin with shallow to deep-water sediments, typically deposited over older accreted sediments and ophiolitic or continental basement. The accretionary prism includes uplifted, strongly deformed rocks scraped off the downgoing oceanic plate on a series of faults. The trench may be several to six miles (up to 10 or more kilometers) deep below the average level of the seafloor in the region and marks the boundary between the overriding and underthrusting plate. The outer trench slope is the region from the trench to the top of the flexed oceanic crust that forms a several hundred to one-thousand-foot (few hundred-meter) high topographic rise known as the forebulge on the downgoing plate.

Trench floors are triangular shaped in profile and typically are partly to completely filled with greywacke-shale turbidite sediments derived from erosion of the accretionary wedge. They may also be transported by currents along the trench axis for large distances, up to hundreds or even thousands of miles (thousands of kilometers) from their ultimate source in uplifted mountains in the convergent orogen.

Flysch is a term that applies to rapidly deposited deep marine syn-orogenic clastic rocks that are generally turbidites. Trenches are also characterized by chaotic deposits known as olistostromes that typically have clasts or blocks of one rock type, such as limestone or sandstone, mixed with a muddy or shaly matrix. These are interpreted as slump or giant submarine landslide deposits. They are common in trenches because of the oversteepening of slopes in the wedge. Sediments that get accreted may also include pelagic sediments initially deposited on the subducting plate, such as red clay, siliceous ooze, chert, manganiferous chert, calcareous ooze, and windblown dust.

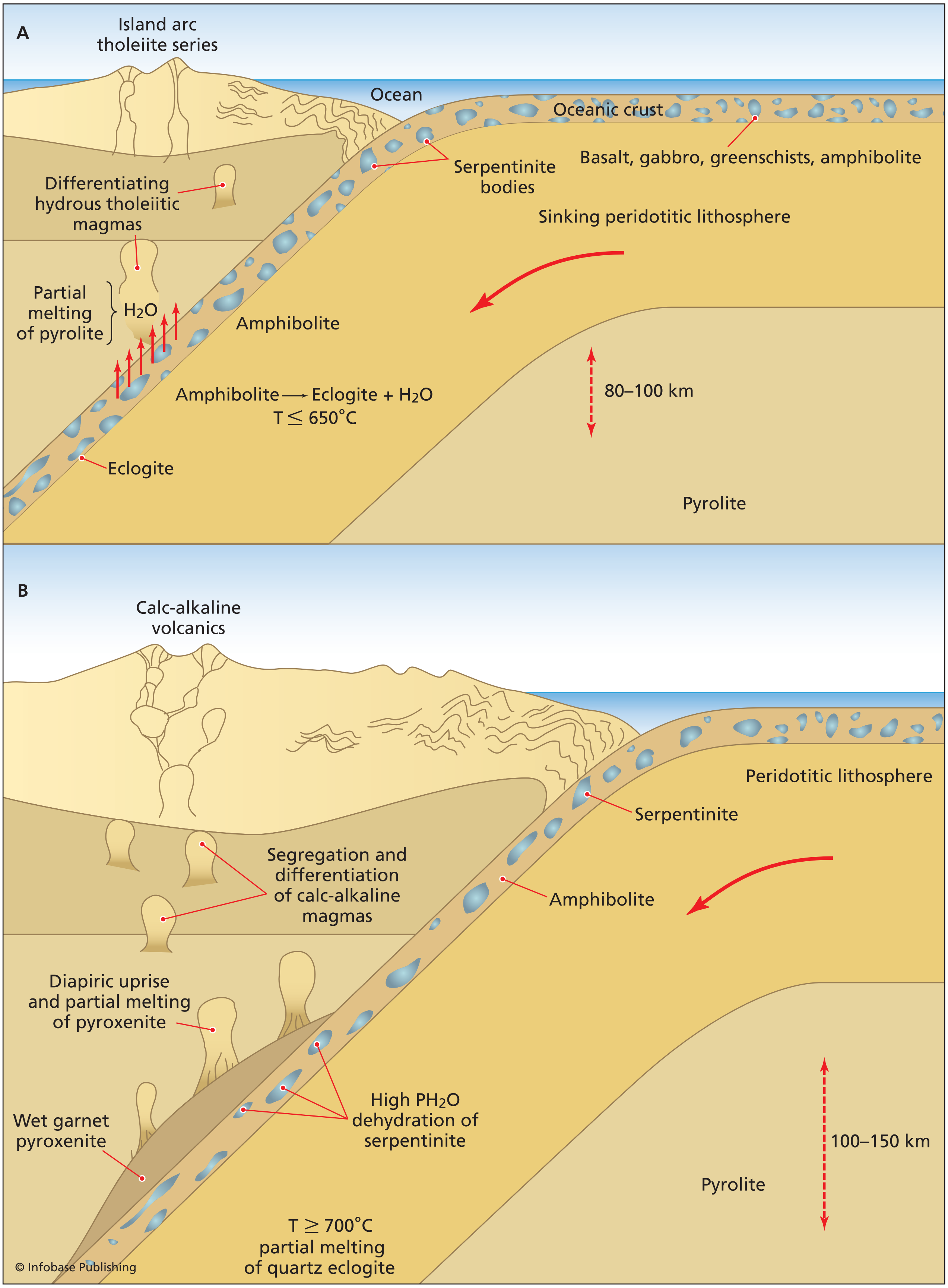
The sediments are deposited as flat-lying turbidite packages, then gradually incorporated into the accretionary wedge complex through folding and the propagation of faults through the trench sediments. Subduction accretion is a process that accretes sediments deposited on the underriding plate onto the base of the overriding plate. It causes the rotation and uplift of the accretionary prism, which is a broadly steady-state process that continues as long as sediment-laden trench deposits are thrust deeper into the trench. Typically new faults will form and propagate beneath older ones, rotating the old faults and structures to steeper attitudes as new material is added to the toe and base of the accretionary wedge. This process increases the size of the overriding accretionary wedge and causes a seaward-younging in the age of deformation.

Parts of the oceanic basement to the subducting slab are sometimes scraped off and incorporated into the accretionary prisms. These tectonic slivers typically consist of fault-bounded slices of basalt, gabbro, and ultramafic rocks, and rarely, partial or even complete ophiolite sequences can be recognized. These ophiolitic slivers are often parts of highly deformed belts of rock known as mélanges. Mélanges are mixtures of many different rock types typically including blocks of oceanic basement or limestone in muddy, shaly, serpentinitic, or even a cherty matrix. Formed by tectonic mixing of the many different types of rocks found in the forearc, mélanges are one of the hallmark rock units of convergent boundaries.

Major differences in processes occur at Andean-style compared to Marianas-style arc systems. Andean-type arcs have shallow trenches, fewer than 3.7 miles (6 km) deep, whereas Marianas-type arcs typically have deep trenches reaching 6.8 miles (11 km) in depth. Most Andean-type arcs subduct young oceanic crust and have very shallow-dipping subduction zones, whereas Marianas-type arcs subduct old oceanic crust and have steeply dipping Benioff zones. Andean arcs have back-arc regions dominated by foreland (retroarc) fold thrust belts and sedimentary basins, whereas Marianas-type arcs typically have back-arc basins, often with active seafloor spreading. Andean arcs have thick crust, up to 43.5 miles (70 km), and big earthquakes in the overriding plate, while Marianas-type arcs have thin crust, typically only 12.5 miles (20 km), and have big earthquakes in the underriding plate. Andean arcs have only rare volcanoes, and these have magmas rich in SiO_2 such as rhyolites and andesites. Plutonic rocks are more common, and the basement is continental crust. Marianas-type arcs have many volcanoes that erupt lava low in silica content, typically basalt, and are built on oceanic crust.

Many arcs are transitional between the Andean or continental-margin types and the oceanic or Marianas types, and some arcs have large amounts of strike-slip motion. The causes of these variations have been investigated and it has been determined that the rate of convergence has little effect, but the relative motion directions and the age of the subducted oceanic crust seem to have the biggest effects. In particular old oceanic crust tends to sink to the point where it has a near-vertical dip, rolling back through the viscous mantle and dragging the arc and forearc regions of overlying Marianas-type arcs with it. This process contributes to the formation of back arc basins.

Much of the variation in the processes that occur in convergent margin arcs can be attributed to the relative convergence vectors between the overriding and underriding plates. In this kinematic approach to modeling convergent margin processes, the underriding plate may converge at any angle with the overriding plate, which itself moves toward or away from the trench. Since the active arc is a surface expression of the 68-mile (110-km) isobath on the subducted slab, the arc will always stay 68 miles (110 km) above this zone. The arc therefore separates two parts of the overriding plate that may move independently, including the frontal arc sliver between the arc and trench and the main part of the overriding plate. The frontal arc sliver is in most cases kinematically linked to the downgoing plate and moves parallel to the plate margin in the direction that contains the oblique component of motion between the downgoing and overriding plate. Different relative angles of convergence between the overriding and underriding plate determine whether or not an arc will have strike-slip motions, and the amount that the subducting slab rolls back (which is age-dependent) determines whether the frontal arc sliver rifts from the arc and causes a back arc basin to open or not. This model helps to explain why some arcs are extensional with big back arc basins, others have strike-slip dominated systems, and others are purely compressional arcs. Convergent margins also show changes in these vectors and consequent geologic

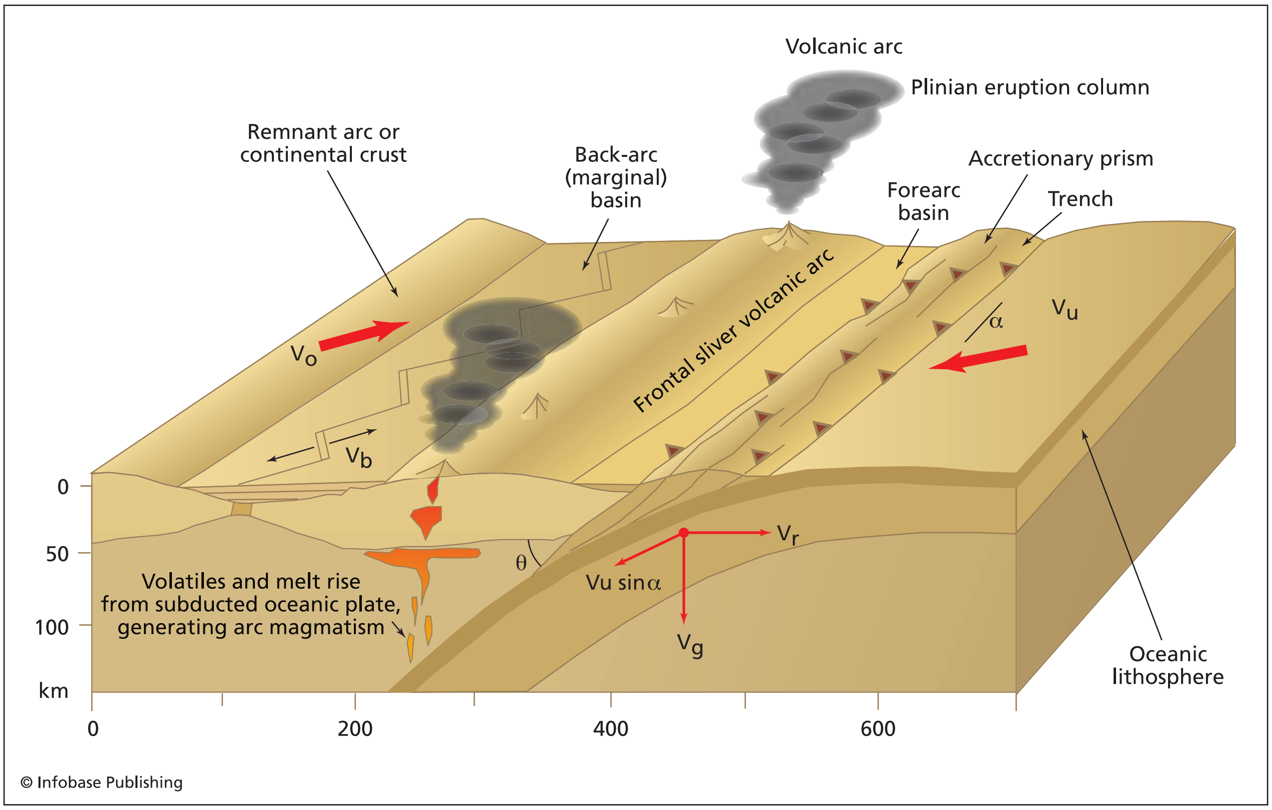


Physiography and geology of arcs: (a) Pacific-type; (b) Andean-type processes with time, often switching quickly from one regime to the other with changes in the parameters of the subducting plate.

The thermal and fluid structure of arcs is dominated by effects of the downgoing slab, which is much cooler than the surrounding mantle and cools the forearc. Fluids released from the slab as it descends past 68 miles (110 km) aid partial melting in the overlying mantle and generate the magmas that form the arc on the overriding plate. This broad thermal structure of arcs results in the formation of paired metamorphic belts, where the metamorphism in the trench environment grades from cold and low-pressure at the surface to cold and high-pressure at depth, whereas the arc records low- and high-pressure high-temperature metamorphic facies series. One of the distinctive rock types found in trench environments is the unusual high-pressure, low-temperature blueschist facies rocks in paleosubduction zones. The presence of index minerals glaucophane (a sodic amphibole), jadeite (a sodic pyroxene), and lawsonite (Ca-zeolite) indicate low temperatures extended to depths of 12–20 miles (20–30 kilometers) (7–10 kilobars [kb]). Since these minerals are unstable at high temperatures, their presence indicates they formed in a low-temperature environment, and the cooling effects of the subducting plate offer the only known environment to maintain such cool temperatures at depth in the Earth.

Forearc basins may include several-kilometer-thick accumulations of sediments deposited in response to subsidence induced by tectonic loading or thermal cooling of forearcs built on oceanic lithosphere. The Great Valley of California is a forearc basin that formed on oceanic forearc crust preserved in ophiolitic fragments found in central California, and Cook Inlet in Alaska is an active forearc basin formed in front of the Aleutian and Alaska range volcanic arc.

The rocks in the active arcs typically include several different facies. Volcanic rocks may include subaerial flows, tuffs, welded tuffs, volcaniclastic conglomerate, sandstone, and pelagic rocks. Debris flows from volcanic flanks are common, and abundant and thick accumulations of ash deposited by winds and dropped by Plinian and other eruption columns may be present. Volcanic rocks in arcs include mainly calc-alkaline series, showing an early iron



Relative motion vectors in arcs. Changes in relative motions can produce drastically different arc geology. Vu = velocity of underriding plate; Vo = velocity of overriding plate; Vb = slip vector between overriding and underriding plates; Vg = velocity of sinking; Vr = velocity of rollback. Note that Vu sin α = velocity of downdip component of subduction, and Vr = Vg cot θ.

Snow-covered Mount Fuji in Japan—a classical, active convergent margin volcano *(AP images)*

enrichment in the melt, typically including basalts, andesites, dacites, and rhyolites. Immature island arcs are strongly biased toward eruption at the mafic end of the spectrum, and may also include tholeiitic basalts, picrites, and other volcanic and intrusive series. More mature continental arcs erupt more felsic rocks and may include large caldera complexes.

Back arc and marginal basins form behind extensional arcs, or may include pieces of oceanic crust trapped by the formation of a new arc on the edge of an oceanic plate. Many extensional back arcs are found in the southwest Pacific, whereas the Bering Sea, between Alaska and the Kamchatka peninsula, is thought to be a piece of oceanic crust trapped during the formation of the Aleutian chain. Extensional back arc basins may have oceanic crust generated by seafloor spreading, and these systems closely resemble the spreading centers found at divergent plate boundaries. The geochemical signature of some of the lavas show some subtle and some not-so-subtle differences, however, with water and volatiles being more important in the generation of magmas in back arc suprasubduction zone environments.

Compressional arcs such as the Andes have tall mountains, reaching heights of more than 24,000 feet (7,315 m) over broad areas. They have little or no volcanism but much plutonism, and typically have shallow dipping slabs beneath them. Andean-type compressional arcs are characterized by thick continental crust with large compressional earthquakes, and show a foreland-style retroarc basin in the back arc region. Some compressional arc segments do not have accretionary forearcs but exhibit subduction erosion during which material is eroded and scraped off the overriding plate, and dragged down into the subduction zone. The Andes show remarkable along-strike variations in processes and tectonic style, with sharp boundaries between different segments. These variations seem to be related to what is being subducted and plate motion vectors. In areas where the downgoing slab has steep dips the overriding plate has volcanic rocks; in areas of shallow subduction there is no volcanism.

COLLISIONS

Collisions are the final products of subduction. There are several general varieties of collisions. They may be between island arcs and continents, such as the Ordovician Taconic Orogeny in eastern North America, or they may juxtapose a passive margin on one continent and an Andean margin on another. More rarely, collisions between two convergent margins occur above two oppositely dipping subduction zones, with a contemporary example extant in the Molucca Sea of Indonesia. Finally, collisions may be between two continents, such as the ongoing India/Asia collision that is affecting much of Asia.

Arc/continent collisions are the simplest of collisional events. As an arc approaches a continent, the continental margin is flexed downward by the weight of the arc, much like a ruler pushed down over the edge of a desk. The flexure induces a bulge a few hundred kilometers wide in front of the active collision zone, and this bulge migrates in front of the collision as a few hundred-meter-high broad topographic high. As the arc terrane rides up onto the continent, the thick sediments in the continental rise are typically scraped off and progressively added to the accretionary prism, with the oldest thrust faults being the ones closest to the arc, and progressively younger thrust faults along the base of the prism. Many forearc regions have ophiolitic basement, and these ophiolites get thrust upon the continents during collision events and are preserved in many arc/continent collisional orogens. The accretionary wedge grows and begins to shed olistostromes into the foredeep basin between the arc and continent, along with flysch and distal black shales. These three main facies migrate in front of the moving arc/accretionary complex at a rate equal to the convergence rate and drown any shallow-water carbonate deposition. After the arc terrane rides up the continental rise, slope, and shelf, it grinds to a halt when isostatic (buoyancy) effects do not allow continued convergence. At this stage a new subduction zone may be initiated behind the collided arc, allowing convergence to continue between the two plates.

Continent/continent collisions are the most dramatic of collisional events, with the current example of the convergence and collision of Africa, Arabia, and India with Europe and Asia affecting much of the continental landmass of the world. Continental collisions are associated with thickening of continental crust and the formation of high mountains, and deformation distributed over wide areas. The convergence between India and Asia dramatically slowed about 38 million years ago, probably associated with initial stages of that collision between 25–40 million years ago. The collision has resulted in the uplift of the Himalayan mountain chain and the Tibetan Plateau, and formed a wide zone of deformation that extends well into Siberia and includes much of Southeast Asia. Since the collision, there has been 2–2.4 inches per year (5–6 cm/yr) of convergence between India and Asia, meaning that a minimum of 775 miles (1,250 km) has had to be accommodated in the collision zone. This convergence has been accommodated in several ways. Two large faults between India and Asia, the Main Central thrust and the Main Boundary thrust, are estimated to have 250 and 120 miles (400 and 200 km) of displacement on them, respectively, so they account for less than half of the displacement. Folds of the crust and general shortening and thickening of the lithosphere may account for some but not a large amount of the convergence. Evidence suggests that underthrusting of the Indian plate beneath Tibet and strike-slip faulting moving or extruding parts of Asia out of the collision zone toward the southwest Pacific accommodated much of the convergence.

The Tibetan Plateau and Himalayan mountain chain are about 375 miles (600 km) wide, with the crust beneath the region being about 45 miles (70 km) thick, twice that of normal continental crust. This has led to years of scientific investigation about the mechanism of thickening. Some models and data suggest that India is thrust under Asia for 600 kilometers, whereas other models and data suggest that the region has thickened by thrusting at the edges and plane strain in the center. In either case the base of the Tibetan crust has been heated to the extent that partial melts are beginning to form, and high heat flow in some rifts on the plateau is associated with the intrusions at depth. The intrusions are weakening the base of the crust, which is starting to collapse under the weight of the overlying mountains, and the entire plateau is on the verge of undergoing extension.

The collisional process is resulting in the formation of a layered differentiated lower continental crust in Tibet, with granitic melts forming a layer that has been extracted from a granulitic residue, along with strong deformation. These processes are not readily observable 30 miles (50 km) beneath Tibet, but are preserved in many old (generally Precambrian) high-grade gneiss terranes around the world thought to have formed in continental collision zones.

Continent/continent collision zones tend to have major effects on global plate motions. Convergence that used to be accommodated between the two continents must be transferred elsewhere on the planet, since all plate motions must sum to zero on Earth. Therefore continental collisions typically cause events elsewhere, such as the formation of new subduction zones and a global reorganization of plate motions.

DESCRIPTIONS OF EARTHQUAKES FROM CONVERGENT MARGINS

The world's largest earthquakes, often called "great" earthquakes, with magnitudes larger than 9, occur along convergent plate margins, especially where one oceanic plate is being subducted beneath a continental plate. This type of configuration leads to huge regions being stressed, or "bent" into a position where regions measuring hundreds of miles (hundreds of km) in length and many tens of miles (km) in depth may suddenly slip in one earthquake event, typically releasing more energy than all the other earthquakes on the planet for many years. For example, the 2004 Sumatra earthquake released more energy than all of the other earthquakes on the planet in the past 30 years. In this section some of these huge convergent margin earthquakes are described to give an understanding of the power of these events in shaping the Earth's surface. In the United States Alaska and the Pacific Northwest are the regions most at-risk for experiencing future convergent margin earthquakes.

Sumatra, 2004 (magnitude 9.0), and Indian Ocean Tsunami

One of the worst natural disasters of the 21st century unfolded on December 26, 2004, following a magnitude 9.0 (some estimates are as high as 9.3, a threefold difference in energy released) earthquake off the coast of northern Sumatra in the Indian Ocean. The earthquake was the largest since the 1964 magnitude 9.2 earthquake event in southern Alaska, and released more energy than all the earthquakes on the planet in the last 25–30 years combined. During this catastrophic earthquake a segment of the seafloor the size of California, lying above the Sumatra subduction zone trench, suddenly moved upward and seaward by several tens of feet. The slip event continued for nearly 10 minutes as the central section of the faulted area moved 65 feet (20 m) and the rupture propagated laterally more than 600 miles (1,000 km). The sudden displacement of this volume of undersea floor displaced a huge amount of water and generated the most destructive tsunami known in recorded history.

Within minutes of the initial earthquake a mountain of water more than 100 feet (30 m) high was ravaging northern Sumatra, sweeping into coastal villages and resort communities with a fury that crushed all in its path, removing buildings and vegetation, and in many cases eroding shoreline areas down to bedrock, leaving no traces of the previous inhabitants or structures. Similar scenes of destruction and devastation rapidly moved up the coast of Indonesia, where residents and tourists were enjoying a holiday weekend. Tsunami waves moved up to 12 miles (20 km) inland in northern Sumatra and elsewhere in Indonesia. Firsthand accounts and numerous videos made of the catastrophe reveal similar scenes of horror, where unsuspecting tourists and residents were enjoying beachfront playgrounds, resorts, and villages, and watched as large breaking waves appeared off the coast. Many moved toward the shore to watch with interest the high surf, then ran in panic as the sea rapidly rose beyond expectations, and walls of water engulfed entire beachfronts, rising tens of feet above hotel lobbies and washing through towns with the force of Niagara Falls. In some cases the sea retreated to unprecedented low levels before the waves struck, inducing many people to move to the shore to investigate the phenomenon; in other cases the sea waves simply came crashing inland without warning. Buildings, vehicles, trees, boats, and other debris were washed along with the ocean waters, forming projectiles that smashed at speeds of up to 30 miles per hour (50 km/hr) into other structures, leveling all in their path and killing nearly a quarter million people.

The displaced water formed a deep-water tsunami that moved at speeds of 500 miles per hour (800 km/hr) across the Indian Ocean, smashing within an hour into Sri Lanka and southern India, wiping away entire fishing communities and causing additional widespread destruction of the shore environment. South of India are many small islands including the Maldives, Chagos, and Seychelles, many of which have maximum elevations of only a few to a few tens of feet above normal sea level. As the tsunami approached these islands many wildlife species and primitive tribal residents fled to the deep forest, perhaps sensing the danger as the sea retreated and the ground trembled with the approaching wall of water. As the tsunami heights were higher than many of the maximum elevations of some of these islands, the forest protected and saved many lives in places where the tsunami caused sea levels to rise with less force than in places where the shoreline geometry caused large breaking waves to crash ashore. The tsunami traveled around the world, being measured as minor (inches) changes in sea level more than 24 hours later in the north Atlantic and Pacific.

Valdez, Alaska, 1964 (magnitude 9.2)

One of the largest earthquakes ever recorded struck southern Alaska at 5:36 P.M. on March 27, 1964, second in the amount of energy released only to the 1960 Chile earthquake. The energy released during the Valdez earthquake was more than the world's largest nuclear explosion and greater than the Earth's total average annual release of seismic energy, yet, remarkably, only 131 people died during this event. Damage is estimated at $240 million (1964 dollars), a remarkably small figure for an earthquake this size. During the initial shock and several other shocks that followed in the next one to two minutes, a 600-mile (1,000 km) long by 250-mile (400 km) wide slab of subducting oceanic crust slipped farther beneath the North American crust of southern Alaska. Ground displacements above the area that slipped were remarkable—much of the Prince William Sound and Kenai Peninsula area moved horizontally almost 65 feet (20 m), and moved upward by more than 35 feet (11.5 m). Other areas more landward of the uplifted zone were down dropped by several to ten feet. Overall almost 125,000 square miles (200,000 km^2) of land saw significant movements upward, downward, and laterally during this huge earthquake.

The ground shook in most places for three to four minutes during the March 27, 1964, earthquake, but lasted for as much as seven minutes in a few places such as Anchorage and Valdez, where unconsolidated sediment and fill amplified and prolonged the shaking. In contrast, ground shaking during the 1906 San Francisco earthquake lasted less than one minute. In the 24 hours after the main earthquake rupture, 28 large aftershocks (10 larger than magnitude 6) hit the region, with epicenters distributed in an area about 50–60 miles (80–100 km) across. The aftershocks continued for months, gradually diminishing in strength but with more than 12,000 aftershocks stronger than 3.5 measured over the next three months.

The shaking caused widespread destruction in southern Alaska, damage as far away as southern California, and induced noticeable effects across the planet. Entire neighborhoods and towns slipped into the sea during this earthquake, and ground breaks, landslides, and slumps were reported across the entire region. A fault near the epicenter broke through the surface, forming a spectacular fault scarp with a displacement of more than 15 feet (3 m), uplifting beach terraces and mussel beds above the high-water mark, many parts of which rapidly eroded to a more stable configuration. Urban areas such as Anchorage suffered numerous landslides and slumps, with tremendous damage done by translational slumps where huge blocks of soils and rocks slid on curved faults down slope, in many cases toward the sea. Houses ended up in neighbors' back yards, and some homes were split in two by ground breaks. The Anchorage neighborhood of Turnagain Heights suffered extensive damage when huge sections of the underlying ground slid toward the sea on a weak layer in the bedrock known as the Bootlegger Shale, which lost cohesion during the earthquake shaking. Tsunamis swept across many towns that had just seen widespread damage by building collapses, washing buildings, vehicles, trains, petroleum tank farms, and anything in their path to higher ground. Near Valdez the tsunami broke large trees, leaving only stumps more than 100 feet (30 meters) above high-tide mark. Other tsunamis swept across the Pacific, destroying marinas as far away as southern California.

The transportation system in Alaska was severely disrupted by the earthquake. All major highways and most secondary roads suffered damage to varying degrees—186 of 830 miles (300 of 1340 km) of roads were damaged, and 83 miles (125 km) of roadway needed replacement. Seventy five percent of all bridges collapsed, became unusable, or suffered severe damage. Many railroad tracks were severed or bent by movement on faults, sliding and slumping into streams, and other ground motions. In Seward, Valdez, Kodiak, and other coastal communities, a series of 3–10 tsunami waves tore trains from their tracks, throwing them onto higher ground. The devastated shipping industry was especially difficult for Alaskans, who had used shipping for more than 90 percent of their transportation needs, and the main industry in the state is fishing. All port facilities in southern Alaska except those in Anchorage were totally destroyed by submarine slides, tsunami, tectonic uplift and subsidence, and earthquake-induced fires. Huge portions of the waterfront facilities at Seward and Valdez slid under the sea during a series of submarine landslides, with the loss of the harbor facilities and necessitating the eventual moving of the cities to higher, more stable ground. Being thrown to higher ground destroyed hundreds of boats, although no large vessels were lost. Uplift in many shipping channels formed new hazards and obstacles that had to be mapped to avoid grounding and puncturing hulls. Downed lines disrupted communication systems, and initial communications with remote communities were taken over by small, independently powered radio operators (if a similar event were to happen today, communications would likely be by cell phone). Water, sewer, and petroleum storage tanks and gas lines were broken, exploded, and generally disrupted by slumping, landslides, and ground movements. Residents were forced to obtain water and fuel that was trucked in to areas for many months while supply lines were restored. Groundwater levels generally dropped, in some cases below well levels, further compounding the problems of access to fresh water.

After the quake many agencies had to coordinate efforts to demolish unrepairable structures, move facilities and even entire communities out of danger zones, and rebuild lost buildings, roads, and railways. Municipal governments, along with state and federal authorities, helped the U.S. Army Corps of Engineers with the reconstruction effort for urban renewal, with the aim of providing affected communities with better land utilization. Some towns, such as Seward, had to be moved completely to higher, more stable ground where entirely new towns were built. Other towns, cities, and rural areas had to reconstruct the infrastructure, including gas pipelines, roads, railroad tracks, and private homes of thousands of people. Soils were tested for liquefaction potential, and homes were moved away from affected locations. Areas with high landslide risks were avoided, as were coastal areas prone to tsunami. All of these efforts led to reconstruction of the communities of southern Alaska, so that now they are safer places to live and work. Since the area is now much more densely populated than it was in 1964, however, future earthquakes that even approach the strength of the 1964 earthquake are likely to do more damage and kill more people than the 1964 catastrophe.

Southern Chile, 1960 (magnitude 9.5)

The largest earthquake ever recorded struck the Concepción area of southern Chile on May 22, 1960. This was a subduction zone earthquake, and a huge section of the downgoing oceanic slab moved during this and related precursors and aftershocks spanning a few days. The main shock was preceded by a large foreshock at 2:45 P.M. on Sunday, May 22, which was fortunate because this foreshock scared most people into the streets and away from buildings soon to collapse. Thirty minutes later at 3:15 P.M., the magnitude 9.5 event struck and affected a huge area of southern Chile, killing an estimated 3,000 to 5,700 people. Another 3,000 were injured and 2 million were left homeless in the huge area devastated by this quake and aftershocks. Massive landslides, slumps, and collapse of buildings occurred throughout the region. The Chilean government estimated property damage to be approximately $300 million. An approximately 600-mile-long by 190-mile-wide (1,000-km-long by 300-km-wide) section of the fault separating the downgoing oceanic slab from the overriding plate slipped, allowing the oceanic plate to sink farther into the mantle. The area that slipped during this event is roughly the size of California.

The main shock from this earthquake generated a series of tsunamis that ravaged the coast of Chile with 80-foot (24-m) tall waves soon after the earthquake, and these waves raced across the Pacific at 200 miles (320 km) per hour, hitting Hawaii, where 61 people were killed and damage was estimated at $75 million. The tsunami then struck Japan, killing 138 and causing another $50 million in damage. Smaller waves hit the west coast of the United States, causing about $500,000 in damage.

One of the more unusual and unexplained events to follow this earthquake was a massive eruption of the Mount Puyehue (Chile) volcano 47 hours after the main shock, presumably triggered in some way by the earthquake. Although the relationships between earthquakes and volcanic eruptions at convergent margins is not understood, recent observations of many volcanoes around the world have noted a correlation between the passage of seismic waves, even from very distant earthquakes, and an increased amount of volcanic activity. Further research is needed to understand these phenomena.

Pakistan, October 8, 2005 (magnitude 7.6)

At 8:50 A.M. on Saturday, October 8, 2005, remote areas of northern Pakistan, north of Islamabad and neighboring Afghanistan, were hit by a major earthquake that caused catastrophic damage to a wide area, largely because of the inferior construction of buildings throughout the region. This earthquake killed more than 86,000 people and injured more than 69,000, leaving about 4 million homeless as the freezing cold of the Kashmir winter set in to the mountainous region. Worst hit was the Muzaffarabad area in Kashmir, where 80 percent of the town was destroyed and more than 32,000 buildings collapsed. Numerous landslides and rock falls blocked mountain roads, so it took many days and even weeks for rescue workers to reach remote areas.

The earthquake was initiated by motion on a thrust fault with the epicenter at 16.2 miles (26 km) depth. The thrust fault is part of a system of faults that formed in response to the collision of India with Asia, forming the Himalayan, Karakoram, Pamir, and Hindu Kush ranges. The Indian plate is moving northward at 1.6 inches (4 cm) per year, and is being pushed beneath the Asian plate, forming the high mountains and Tibetan plateau. Slip on a number of faults accommodates this plate motion and has formed a series of northwest-southeast striking-thrust faults in the Muzaffarabad area. These faults deform young Pleistocene alluvial fans into anticlinal ridges, showing that deformation in the region is active and intense, and the region is likely to suffer additional strong earthquakes.

Chi-Chi, Taiwan, 1999 (magnitude 7.3)

On September 21, 1999, a magnitude 7.3 earthquake struck the area near Chi Chi in western Taiwan, causing widespread destruction across the island. A 53-mile (85-km) long segment of the Cher-Lung Pu thrust fault ruptured at 1:47 A.M. when most people were sleeping, moving laterally up to 33 feet (10 m) and vertically up to 32 feet (9.8 meters) within 60 seconds. The earthquake released an amount of energy roughly equivalent to 30 times that released by the atomic bomb dropped on Hiroshima, and was the largest earthquake to strike the island in a century. There were 2,333 documented deaths and more than 10,000 people were injured, plus more than 100,000 homes destroyed, with total economic losses topping $14 billion.

The Chi Chi earthquake was associated with many ground ruptures and surface displacement features, even though the epicenter was located five miles (8 km) below the western foot of the Western Foothill Mountains of Taiwan. New waterfalls were created where the fault rupture crossed rivers, and bridge spans collapsed from movement on unstable riverbanks, and buildings on one side of the scarps were suddenly raised several tens of feet about their neighbors. Landslides and slumps tilted and destroyed many other buildings, typically sending riverfront buildings crashing into the riverbeds. In one example more than 1,060,000,000 cubic feet (30 million m^3) of a mountain slope slid in the Jiu-Feng Er Shan slide, killing 42 people. Miraculously a woman and two children were carried more than half a mile (1 km) downhill in the landslide but survived unscratched. In many places sand and even gravel boiled up from liquefaction of buried sediments, forming ridges and sand volcanoes. Near the Ta-An River along the front of the mountains, the slopes of the mountains were changed, forming a new anticline above the thrust fault. The Shih-Kang Dam along the Ta-Chia River collapsed where a strand of the fault crossed the spillways, and the southern side of the dam was raised more than 30 feet (9.8), destroying the water-supply system for Tai Chung County. Numerous buildings collapsed, but often where one building crumbled, the one adjacent to it was barely damaged. Earthquake engineers have studied the structural differences between buildings to improve building codes in the region.

Bam, Iran, 2003 (magnitude 6.7)

Iran sits in the zone of convergence between the Arabian and Asian plates and has numerous mountain ranges that formed by folding and faulting of the rocks in the collision zone. There are many earthquakes in Iran, some of which are extremely destructive and have killed many people. For instance, in 893 an earthquake in Ardabil Iran killed an estimated 150,000 people, and other deadly earthquakes have stricken most regions of Iran, including the capital, Tehran. On December 26, 2003, the ancient Silk Road walled city and citadel of Bam, Iran, was leveled by a magnitude 6.7 earthquake that struck at 5:27 A.M., killing an estimated 27,000–50,000 people and injuring more than 20,000. Bam was in a region characterized by high seismicity and many earthquakes. In fact Bam had survived larger earthquakes in the past during its 2,000-year history without being destroyed, so many scientists were puzzled why a moderate-sized earthquake would totally destroy the city.

The earthquake was preceded by foreshocks on the afternoon of December 25, but since this area is characterized by high seismicity, residents were not alarmed and did not prepare for what was to come. Many of Bam's residents returned home on Thursday evening, December 25, for the Friday holiday, and were woken at 4:00 A.M. on Friday morning by a strong foreshock that sent many residents into the streets. All seemed calm after a short while, so the residents returned indoors, and most were sleeping at 5:27 A.M., when the main earthquake hit, releasing most of its energy directly below Bam, leveling most of the ancient city that had withstood many earthquakes, drought, and seizure by roving warriors including Genghis Khan. Bam was the oldest walled city, originally founded during the Sassanian period (250 B.C.E.), but much was built in the 12th century, and more in the Safavid period between 1502 and 1722. The walled city included about 4 square miles (6 km^2), including more than 10,000 buildings, and was surrounded by 38 towers. Most of the buildings were made of mud bricks, clay, and straw and were not reinforced; hence when the shaking was most intense, these buildings collapsed, burying the residents inside.

Why was Bam destroyed by a magnitude 6.7 earthquake, when it had survived larger earthquakes in the past? This example illustrates that every earthquake is different in terms of where and how its energy is released, and Bam had been fortunate in the past. This event was relatively shallow, and the earthquake focus (the point where the energy was first released) was below Bam. The energy was focused, or directed, by surrounding rock structure directly at the old city, much like sound can be focused or directed by cupping one's hand around the mouth, or by walls in a city or canyons in the wilderness. This earthquake released most of its energy directly toward Bam, destroying the city.

Kobe, Japan, 1995 (magnitude 6.9)

The industrial port city of Kobe, Japan, was hit by history's costliest earthquake ($100 billion in property damage) at 5:46 A.M. on January 17, 1995. The 30-mile (50-km) long fault rupture passed directly through the world's third-busiest port and home to 1.5 million people. With little warning 6,308 died in Kobe before sunrise on that cold January morning. The rupturing event lasted 15 seconds, moved each side of the fault more than six feet (1.7 m) horizontally relative to the other side, and uplifted the land by three feet (1 m). The many areas of unconsolidated sediment in and around Kobe saw some of the worst damage, and shook for as long as 100 seconds because of the natural amplification of the seismic waves. Liquefaction was widespread and caused much of the damage, including collapse of buildings and port structures and destruction of large parts of the transportation network. Water, sewer, gas, and electrical systems were rendered useless. More than 150,000 buildings were destroyed in the initial quake, and a huge fire that started from ruptured gas lines consumed the equivalent of 70 square blocks.

These examples of convergent margin earthquakes show that the strongest, deadliest earthquakes tend to occur at convergent margins. Areas thousands of miles (km) long can suddenly slip in one large earthquake event, generating fast-moving seismic waves, giant tsunamis, landslides, shifts of land level, and indirect effects such as fires, disease, and loss of livelihood for millions. Convergent margin earthquakes are capable of releasing more energy than any other catastrophic Earth event, and are therefore among the most destructive forces of nature. When considered with the volcanic eruptions that characterize many sections of convergent margins it is clear that these beautiful, mountainous areas are among the most hazardous on Earth.

See also ACCRETIONARY WEDGE; CONTINENTAL CRUST; DEFORMATION OF ROCKS; GRANITE, GRANITE BATHOLITH; ISLAND ARCS, HISTORICAL ERUPTIONS; METAMORPHISM AND METAMORPHIC ROCKS; PLATE TECTONICS; STRUCTURAL GEOLOGY; VOLCANO.

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Copernicus, Nicolaus (1473–1543) Prussian (Polish or German, disputed) *Astronomer, Mathematician, Physician, Economist, Military Leader, Diplomat* Nicolaus Copernicus is credited with being one of the earliest scientists to propose a scientifically sound model with the Sun as the center of the universe, displacing the Earth from this role in earlier models. His heliocentric model was described in his book *De revolutionibus orbium coelestium* (*On the Revolutions of the Celestial Spheres,* 1939), which many regard as the starting point of modern astronomy and the beginning of a revolution in science known as the Copernican revolution.

EARLY YEARS

Nicolaus Copernicus was born on February 19, 1473, in Toruń, a town on the Vistula River in what is now Poland. His father was a copper trader from Kraków, and his mother, Barbara Watzenrode, was from a wealthy merchant family in Toruń. Nicolaus's father died when he was 10 or 12, at which point his maternal uncle, Lucas Watzenrode the Younger, who became archbishop of Warmier, raised Nicolaus through his school years.

In 1491 Copernicus began his college years by enrolling in the Kraków Academy (the contemporary Jagiellonian University), where he began his studies in astronomy. After four years of study at Kraków, Copernicus returned to Toruń, then moved to the Universities of Bologna and Padua, where he studied law and medicine, supported financially by his uncle Watzenrode the Younger.

SCIENTIFIC CONTRIBUTIONS

After completing his studies, Nicolaus Copernicus returned to Prussia and took on the position of secretary to his uncle Lucas Watzenrode, who was at the time the bishop of Warmia. During this time he lived at the bishop's castle at Lidzbark Warminski (Heilsberg) and started his research on the heliocentric model of the universe. Copernicus obtained a position as a burgher of Warmia in the Collegiate Church of the Holy Cross in Wroclaw (Breslau) in Bohemia, and he kept this position for most of his life while carrying out his studies as an amateur astronomer. Copernicus was a polymath, serving as economic administrator of Warmia from 1516 to 1521, and as head of the Royal Polish forces for Olsztyn (Allenstein) castle when it was besieged by the Teutonic Knights during the Polish-Teutonic War of 1519–21. He also worked as a diplomat on behalf of the bishop of Warmia and adviser to Duke Albert of Prussia, especially in the fields of monetary reforms, where he was charged with determining and negotiating who had the right to mint coins. Copernicus was also called on for his medical skills, even diagnosing and saving the life of one of Duke Albert's counselors.

Copernicus is most famous for proposing the heliocentric model of the universe. He first formulated it in a six-page, handwritten text, the "Commentariolus" (Little Commentary), preceding his famous six-volume work, *De revolutionibus orbium coelestium,* published in 1543 over three decades or more, although the exact date of the "Commentariolus" is not known. "Commentariolus" contained seven main assumptions:

- There is no one center for all the celestial circles or spheres.
- The center of the Earth is not the center of the universe, but only of gravity and of the lunar sphere.
- All the spheres revolve about the Sun as their midpoint, and therefore the Sun is the center of the universe.

- The ratio of the Earth's distance from the Sun to the height of the firmament (the heavens) is so much smaller than the ratio of the Earth's radius to its distance from the Sun that the distance from the Earth to the Sun is imperceptible in comparison with the height of the firmament.
- Whatever motion appears in the firmament arises not from any motion of the firmament, but from the Earth's motion. The Earth together with its circumjacent elements performs a complete rotation on its fixed poles in a daily motion, while the firmament and highest heaven abide unchanged.
- What appear to observers on Earth as motions of the Sun arise not from its motion but from the motion of the Earth and its sphere, which revolves about the Sun like any other planet. The Earth has, then, more than one motion.
- The apparent retrograde and direct motion of the planets arises not from their motion but from the Earth's. The motion of the Earth alone, therefore, suffices to explain so many apparent inequalities in the heavens.

In the period between the publication of his two major works, Copernicus's ideas were discussed among many scholars and clergy of the time, including the archbishop of Capua, Nicholas Shonberg, who encouraged Nicolaus to communicate his work and discoveries to scholars and to share his writings at the earliest possible moment.

While Copernicus was still finishing *De revolutionibus orbium coelestium,* a student of mathematics named Georg Joachim Rheticus came to work with him, as arranged by Phillip Melanchton, a professor from Prussia (later part of Germany). Over a period of two years Rheticus studied with Copernicus and wrote a book about Copernicus's work, *Narratio prima* (First account), which many scholars read who as a result began to appreciate Copernicus's works. Rheticus followed this in 1542 with a well-received book on trigonometry outlining Copernicus's ideas in this field. Having seen his ideas generally well accepted and not criticized by the clergy at the time, Copernicus agreed to publish his major works through the printer Johannes Petreius in Nuremberg. He published *De revolutionibus orbim coelestium* in 1543 in six volumes categorized by the following:

- general vision of the heliocentric theory, and a summarized exposition of his idea of the world
- mainly theoretical, presents the principles of spherical astronomy and a list of stars (as a basis for the arguments developed in the subsequent books)
- mainly dedicated to the apparent motions of the Sun and to related phenomena
- description of the Moon and its orbital motions
- concrete exposition of the new system

Copernicus died after a long illness on May 24, 1543, the same year that his treatise was published. Legend has it Copernicus awoke from a stroke-induced coma and looked at his book as it was placed in his hands, then died peacefully. He was buried at Frombork Cathedral in northern Poland.

Copernicus's ideas were not only revolutionary, but were quite different from those advocated by the Catholic Church. Despite this, the books caused only minor controversy at first, until three years later in 1546, when Giovanni Maria Tolosani, a Dominican priest, denounced the work, stating that it would have been condemned earlier if the chief censor of the Catholic Church at the time (Bartholomeo Spina) had not died while reviewing it. In 1616 the Roman Catholic Church issued a decree that suspended *De revolutionibus orbim coelestium* until it could be corrected, on the basis that it opposed Holy Scripture. The Italian astronomer Galileo Galilei (1564–1642), who supported Copernicus's ideas, was investigated by Cardinal Bellamine on the orders of Pope Paul V and in 1633 was convicted of grave suspicion of heresy for "following the position of Copernicus, which is contrary to the true sense and authority of Holy Scripture" (Papal Condemnation [Sentence] of Galileo, June 22, 1633 [translated from the Latin], in Giorgio de Santillana, *The Crime of Galileo,* University of Chicago Press, 1955). Galileo was placed under house arrest for the rest of his life. The church's influence was strong in this era—another follower of Copernicus's ideas, Giordano Bruno, was condemned and burned at the stake on February 17, 1600, for being a heretic. The censorship of Copernicus's views continued for centuries, with the original *De revolutionibus orbim coelestium* remaining on the Index of Prohibited Books published by the Catholic Church in 1758. The revolutionary book was finally dropped in the 1835 edition of prohibited works, nearly 300 years after its initial publication.

See also ASTRONOMY; GALILEI, GALILEO; SOLAR SYSTEM.

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coral Corals are invertebrate marine fossils of the phylum Cnidaria characterized by radial symmetry and a lack of cells organized into organs. They are related to jellyfish, hydroids, and sea anemones, all of which possess stinging cells. Corals are the best preserved of this phylum because they secrete a hard, calcareous skeleton. The animal is basically a simple sac with a central mouth, surrounded by tentacles, that leads to a closed stomach. Cnidarians are passive predators, catching food that wanders by in their tentacles. Corals and other cnidarians produce alternating generations of two body forms. Medusae are forms that reproduce sexually to form polyps, the asexual forms from which the medusae may bud. Corals belong to a subclass of the anthozoan cnidarians known as the Zooantharia. The jellyfish belong to the Scyphozoa class, and the Hydrozoa class includes both fresh- and saltwater cnidarians dominated by the polyp stage.

Corals can live in a range of conditions from shallow tidal pools to 19,700 feet (6,000 m) depth. They have a cylindrical or conical skeleton secreted by the polyp-stage organism, which lives in the upper exposed part of the structure. The skeleton is characterized by radial ridges known as septa that join the skeleton's outer wall (the theca), and may have flat floors that were periodically secreted by the polyp.

Corals range from the Early Ordovician Tabulata forms, joined in the Middle Ordovician by the rugose corals. They both experienced a major extinction in the Late Devonian, from which the rugose forms recovered stronger. Both forms became extinct in the Early Triassic and were replaced by modern coral forms known as Scleractinia, which apparently arose independently from different soft-bodied organisms.

Most corals grow in colonial communities and form reefs that provide numerous advantages, including shelter for larvae and young stages. Reefs are framework-supported carbonate mounds built by carbonate-secreting organisms, or in some instances

Coral reef in the Red Sea, Egypt *(Specta, Shutterstock, Inc.)*

any shallow ridge of rock lying near the surface of the water. Reefs contain a plethora of organisms that together build a wave-resistant structure that reaches up to just below the low-tide level in the ocean waters and provide shelter for fish and other organisms. The spaces between the framework are typically filled by skeletal debris, which together with the framework become cemented together to form a wave-resistant feature that shelters the shelf from high-energy waves. Modern corals can survive only in shallow waters that range in temperature from 77 to 84°F (25–29°C), at depths of fewer than 300 feet (90 m). Reef organisms (presently consisting mainly of zooxanthellae) can survive only in the photic zone, so reef growth is restricted to the upper 328 feet (100 m) of the seawater. Reefs have various forms including fringing, barrier, and atoll reefs.

Reefs are built by a wide variety of organisms, including red algae, mollusks, sponges, and cnidarians (including corals). The colonial scleractinia corals are presently the principal reef builders, producing a calcareous external skeleton characterized by radial partitions known as septa. Inside the skeleton are soft-bodied animals called polyps, containing symbiotic algae that are essential for the life cycle of the coral and for building the reef structure. The polyps contain calcium bicarbonate that is broken down into calcium carbonate, carbon dioxide, and water. The calcium carbonate is secreted to the reefs building its structure, whereas the algae photosynthesize the carbon dioxide to produce food for the polyps.

There are several different types of reefs, classified by their morphology and relationship to nearby landmasses. Fringing reefs grow along and fringe the coast of a landmass and are often discontinuous. They typically have a steep outer slope, an algal ridge crest, and a flat, sand-filled channel between the reef and the main shoreline. Barrier reefs form at greater distances from the shore than fringing reefs and are generally broader and more continuous than fringing reefs. They are among the largest biological structures on the planet—for instance, the Great Barrier Reef of Australia is 1,430 miles (2,300 km) long. A wide, deep lagoon typically separates barrier reefs from the mainland. All these reefs show a zonation from a high-energy side on the outside or windward side of the reef, and typically grow fast, and have a smooth outer boundary. In contrast the opposite side of the reef receives little wave energy and may be irregular, poorly developed, or grade into a lagoon. Many reefs also show a vertical zonation in the types of organisms present, from deep water to shallow levels near the sea surface.

Atolls or atoll reefs form circular-, elliptical-, or semicircular-shaped islands made of coral reefs that rise from deep water; atolls surround central lagoons, typically with no internal landmass. Some atolls do have small central islands, and these, as well as parts of the outer circular reef, are in some cases covered by forests. Most atolls range in diameter from half a mile to more than 80 miles (1–130 km) and are most common in the western and central Pacific Ocean basin and in the Indian Ocean. The outer margin of the semicircular reef on atolls is the most active site of coral growth, since it receives the most nutrients from upwelling waters on the margin of the atoll. On many atolls coral growth on the outer margin is so intense that the corals form an overhanging ledge from which many blocks of coral break off during storms, forming a huge *talus* slope at the base of the atoll. Volcanic rocks, some of which lie more than half a mile (1 km) below current sea level, underlie atolls. Since corals can grow only in shallow water fewer than 65 feet (20 m) deep, the volcanic islands must have formed near sea level, grown coral, and subsided with time, with the corals growing at the rate that the volcanic islands were sinking.

Charles Darwin proposed such an origin for atolls in 1842 based on his expeditions on the *Beagle* from 1831 to 1836. He suggested that volcanic islands were first formed with their peaks exposed above sea level. At this stage coral reefs were established as fringing reef complexes around the volcanic island. He suggested that with time the volcanic islands subsided and were eroded, but that the growth of the coral reefs kept up with the subsidence. In this way as the volcanic islands sank below sea level, the coral reefs continued to grow and eventually formed a ring circling the location of the former volcanic island. When Darwin proposed this theory in 1842, he did not know that ancient eroded volcanic mountains underlay the atolls he studied. More than 100 years later, drilling confirmed his prediction that volcanic rocks would be found beneath the coralline rocks on several atolls.

With the advent of plate tectonics in the 1970s, the cause of the subsidence of the volcanoes became apparent. When oceanic crust is created at midocean ridges, it is typically about 1.7 miles (2.7 km) below sea level. With time, as the oceanic crust moves away from the midocean ridges, it cools and contracts, sinking to about 2.5 miles (4 km) below sea level. In many places on the seafloor small volcanoes form on the oceanic crust a short time after the main part of the crust formed at the midocean ridge. These volcanoes may stick above sea level a few hundred meters. As the oceanic crust moves away from the midocean ridges, these volcanoes subside below sea level. If the volcanoes happen to be in the tropics where corals can grow, and if the rate of subsidence is slow enough for the growth of corals to keep up with subsidence, then atolls may form where the volcanic island used to be. If corals do not grow or cannot keep up with subsidence, then the island subsides below sea level and the top of the island gets scoured by wave erosion, forming a flat-topped mountain that continues to subside below sea level. These flat-topped mountains are known as guyots, many of which were mapped by military surveys during exploration of the seafloor associated with military operations of World War II.

Reefs are extremely sensitive and diverse environments, and cannot tolerate large changes in temperature, pollution, turbidity, or water depth. Reefs have also been subject to mining and destruction for navigation, and have even been sites of testing nuclear bombs in the Pacific. Thus, human-induced and natural changes in the shoreline environment pose a significant threat to the reef environment.

Reefs are rich in organic material and have high primary porosity, so they are a promising target for many hydrocarbon exploration programs. Reefs are well represented in the geological record, with examples including the Permian reefs of west Texas; the Triassic of the European Alps, the Devonian of western Canada, Europe, and Australia; and the Precambrian of Canada and South Africa. Organisms that produced the reefs have changed dramatically with time, but, surprisingly, the gross structure of the reefs has remained broadly similar.

See also DIVERGENT PLATE MARGIN PROCESSES.

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Coriolis, Gustave (1792–1843) French *Mathematician, Engineer, Scientist* Gustave Coriolis, also known as Gaspard-Gustave de Coriolis, was born on May 21, 1792, son of Jean-Baptiste-Elzéar Coriolis and Marie-Sophie de Maillet. He is best known for his work on the Coriolis force caused by the Earth's rotation, but also was the first person to define work as the product of force times distance, and he defined kinetic energy as it is used in the current scientific meaning. He died on September 19, 1843, at the age of 51, in Paris, while he was a professor at the École Centrale Paris.

Gustave's father was a military officer who served with Louis XVI in 1790. This caused difficulties for the family during the French Revolution when the king was caught while attempting to flee Paris and was returned to the capital, where he was guillotined in January 1793. Gustave's family fled to Nancy, where his father became an industrialist, while the son attended schools. In 1808 he entered the École Polytechnique and on graduating entered the École des Ponts et Chaussées in Paris. For the next few years Coriolis worked with the engineering corps in the Meurthe-et-Moselle district in the Vosges Mountains, and after his father died he worked long hours to raise money to support his family, even though his health was failing.

Coriolis became a tutor at the École Polytechnique in 1816, where he experimented on fricton and hydraulics, publishing a textbook in 1829, *Calcul de l'effet des machines* (Calculation of the effect of machines), describing the science of mechanics in a way that industry could apply. The same year Coriolis took the position of professor of mechanics at the École Centrale des Arts et Manufactures in Paris, and in 1832 he took on a position at the École des Ponts and Chaussées and was elected to the Academie des Sciences. Coriolis spent much of his time over the next years working on the principles of kinetic energy as applied to rotating systems and eventually published his famous paper in 1835 "Sur les équations du mouvement relatif des systèmes de corps" (On the equations of relative motion of a system of bodies), relating to the transfer of energy in rotating systems such as gears and waterwheels. In 1838 Coriolis ended his teaching career and became director of studies, but in spring 1843 his poor health took a dramatic turn for the worse, and he died in early fall of that year.

Gustave Coriolis did not work directly with the forces in the atmospheric system, yet by the end of the 19th century his work was being applied to ideas about the ceneral circulation of the atmosphere and relationships between atmospheric pressure and winds. He is recognized for this contribution since he showed that the laws of motion could be applied to a rotating frame of reference if an extra force, now called the Coriolis acceleration, is added to the equations of motion.

See also ATMOSPHERE; CORIOLIS EFFECT.

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Coriolis effect The Coriolis effect, or force, produces a deflection of moving objects and currents to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The force ranges from zero at the equator to a maximum at the poles and can be understood by considering the rotation of the Earth from a position above the poles. If we look down from above the North Pole, the rotation appears to be counterclockwise, and from above the South Pole it appears to be clockwise. Points on or very near the poles do not have to travel far during one rotation of the Earth about its axis because the circular path traveled has a relatively small diameter, whereas points that lie on the equator must speed through space at 1,000 miles per hour (1,600 km/hr) to complete a rotation, traveling a distance approximately the length of the Earth's diameter within 24 hours.

As air and water move poleward from the equatorial regions, they bring with them the higher velocity they acquired while traveling closer to the equator. The slower speeds of rotation of the Earth under the moving air and water cause these fluids to move a greater distance per unit time than the underlying Earth, and this results in a deflection to the right in the Northern Hemisphere, and to the left in the Southern Hemisphere. Likewise, air and water moving from the poles to the equator will be moving slower than the underlying Earth, this time causing the Earth to move more per unit time than the air or water. This again causes a deflection to the right in the Northern Hemisphere, and to the left in the Southern Hemisphere.

See also ATMOSPHERE; CORIOLIS, GUSTAVE.

cosmic microwave background radiation

In 1964 two American scientists, Arno Penzias and Robert Wilson, were working on a project at Bell Laboratories in New Jersey to identify and eliminate sources of interference with satellite communications. In their work they accidentally stumbled on one of the most important finds in astronomy and astrophysics of the century. While Penzias and Wilson were examining the radiowave emissions from the Milky Way Galaxy using microwave wavelengths, they discovered a background "hiss" that would not go away, no matter which direction they pointed their receiving antenna or when they took the measurements. They then showed that this background hiss persisted throughout the year and was isotropic, meaning it had the same intensity in all directions.

Penzias and Wilson labored over ways to explain this noise in the radio signal, seeking explanations ranging from short circuits and equipment malfunction, to ground interference, atmospheric storms, and everything else they and their colleagues could think of as possible causes. All of these simple explanations failed, and in the end Penzias and Wilson concluded that this low-level noise signal was a remnant of the radiation left over from the initial big bang and the creation of the universe. They presented the results of their findings and analysis, and won the 1978 Nobel Prize in physics.

The background hiss at microwave wavelengths that Penzias and Wilson discovered became known as the cosmic microwave background radiation. Such a signal had been predicted to exist by physicists since the 1940s, and more specifically by Princeton University researchers in the early 1960s. These predictions were based on the idea that the early universe after the big bang must have been extremely dense and hot, and filled with high-energy thermal radiation including short-wavelength gamma rays. In the papers published before Penzias and Wilson's discovery, scientists predicted that as the universe expanded and cooled, the frequency of this primordial background radiation would have shifted from gamma rays, to X-rays, to ultraviolet rays, and eventually to radio waves. This became known as theoretical black body radiation, with its frequency decreasing as the body (the universe) cooled and expanded. As other scientists, including the Princeton group, examined the discovery of Penzias and Wilson, they determined that the temperature of the present-day cosmic background radiation corresponds to a black body with a temperature of about 3 kelvin.

Some wavelengths of the cosmic background radiation are difficult to measure from the Earth. Scientists spent years of research trying to make better measurements of this radiation, using observation platforms including high-flying balloons, and designed other experiments that were never completed. In 1989, however, the satellite *Cosmic Background Explorer* (COBE) was launched, and it measured the intensity of the cosmic background radiation at different wavelengths, verifying that it corresponded to a black body radiation curve for a body with a temperature of 2.7 kelvin. COBE also verified that the background radiation is highly isotropic, or uniform in different directions. But COBE detected a very slight shift of the radiation toward the blue in the direction of the constellation Leo, and toward the red in the exact opposite direction. These shifts were equated with Doppler shifts of the background radiation caused by the motion of the Earth in space. Motion causes radiation to shift toward shorter and hotter wavelengths (blue) toward the direction the body (Earth) is moving, caused by the contraction of the incoming radiation, and to the red (cooler) in the opposite direction, as the radiation has to travel a little farther to get to the new position of the Earth as it moves. The Doppler shifts (0.0034 kelvin) of the cosmic background radiation correspond to motion of the Earth through space of 248 miles/sec (400 km/sec) toward the constellation Leo.

Since radiation cannot travel faster than the speed of light, and the cosmic background radiation is coming from so far away, the 3-kelvin radiation now observed from Earth (or Earth orbit) was emitted far back in time, almost from the time of the beginning of the universe. The photons now being received on Earth as this cosmic background radiation have not interacted with any matter since the universe was only about 100,000 years old (some 13 or 14 billion years ago), and when the universe was less than 1/1,000 of its present size. At present this is about the furthest back in time and space that can be observed without entering the fields of nuclear and particle physics. The cosmic background radiation represents the oldest snapshot of how the universe looked when it was young.

See also ASTRONOMY; ASTROPHYSICS; ORIGIN AND EVOLUTION OF THE UNIVERSE.

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cosmic rays Extremely energetic particles that move through space at close to the speed of light are known as cosmic rays. Some cosmic rays are so energetic that they can have energies of about 10^{20} electron volts, much greater than the 10^{13} electron volts that can be produced by particle accelerators on Earth. Most cosmic rays are made of atomic nuclei, about 90 percent of which are bare hydrogen nuclei (protons), 9 percent are helium nuclei (alpha particles), and about 1 percent are electrons (beta minus particles), but cosmic rays include a whole range of particles that spans the entire periodic table of the elements. The name *ray* as applied to cosmic rays is a misnomer, since these particles act individually, not as rays or beams.

The Austrian-American physicist Victor Hess discovered cosmic rays in 1912. There are several different classes of sources for cosmic rays. Galactic cosmic rays come from outside the solar system, with most originating from explosive processes in other stars of the Milky Way Galaxy. These sources can include neutron stars, supernovas, and black holes. Other galactic cosmic rays come from the most distant parts of the visible universe, particularly the cosmic rays with very high energy. Supernovas can produce cosmic rays with energies up to 10^{14} electron volts, but other, more energetic processes must be the source of the very high-energy particles. The source of these very high-energy particles was unknown until observations by a team from 17 countries from the Pierre Auger International Cosmic Ray Observatory in Mendoza, Argentina, identified the most likely source for these particles to be from active galactic nuclei. Solar cosmic rays, which consist mostly of protons and alpha particles, are ejected from the Sun during solar flare events and generally have lower energy than galactic cosmic rays. Also known as solar energetic particles, they have a composition similar to that of the Sun and overlap in their phases with the solar wind.

Cosmic rays constantly bombard the surface of the Earth, and the flux, or flow rate, of these subatomic particles is controlled by the background amount of particles, the solar wind, and the Earth's magnetic field. The magnetized plasma of the solar wind decelerates incoming cosmic ray particles and partially excludes those with energies of less than 1 giga electron volt (GeV, equal to 10^9 electron volts, about equal to the mass equivalent of one atomic unit). The 11-year cycle of solar activity means that the solar wind is not constant over time—the modulating effect of the solar wind on the flux of cosmic rays changes with time. The Earth's magnetic field also modifies and deflects cosmic rays, as confirmed by the fact that the flux shows variation in intensity based on latitude, longitude, and azimuth (direction of approach), and with polarity of the magnetic field. More cosmic rays hit the Earth at the magnetic poles than at the equator, since the magnetic field lines tend to move the charged particles in the direction of the field and not across them, as would happen at the equator.

Cosmic rays can be detected on the Earth by tracing their tracks in specially designed liquid-filled devices called bubble chambers or with a number of other detection instruments. Bubble chambers work on the principle that the cosmic rays are electrically charged; their passage through a special liquid-filled container leaves a trail of bubbles whose length and shape are related to the charge and speed of the particles. Cosmic rays travel at close to the speed of light in the low density of interstellar space. When they approach the Earth, they interact with matter such as atmospheric gases, forming collisions that then form pions, kaons, and mesons, all of which are subatomic particles that rapidly decay into muons, which may reach the Earth's surface. Muons are ionizing radiation, and they are detected by devices such as the bubble chambers and scintillation detectors. They can also be measured in high-altitude particle detectors where the muons interact with special plastics that are then etched to reveal their tracks.

Cosmic rays can interact with some electronics, even changing the states of elements in integrated circuits, leading to corrupted data and transient errors in electronic devices, especially in high-altitude devices such as satellites. While the radiation received from cosmic rays by people on Earth is very small, this would increase for any long-term space travelers, posing a potentially serious obstacle to long-distance space travel for humans.

See also ASTRONOMY; BLACK HOLES; ORIGIN AND EVOLUTION OF THE UNIVERSE; SUPERNOVA.

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cosmology Cosmology is the study of the structure and evolution of the universe. Cosmologists seek answers to questions such as how big and how old is the universe, what is its structure on small and large scales, and what is its history and fate—will it expand forever, or collapse back on itself? Cosmology encompasses topics including understanding the life cycles of stars and galaxies, the formation of matter, and the natural laws that hold the universe together.

To study the universe and its history, it is first necessary to make some basic observations. The first is that the universe has structure and order, at every scale observable, from subatomic particles to the distribution of galactic clusters. This order means that laws of nature are being followed that control this structure (an alternative way to view this is that the laws of nature that we construct are our best attempt to explain the observable universe). One interesting observation about the order of the universe is that matter is clustered at scales ranging from subatomic particles to superclusters of galaxies. At the largest scales of observation, however, covering huge expanses of the universe, it becomes clear that the distribution of matter becomes homogeneous at huge distances. Said another way, each area of universe that is about 200–300 megaparsecs across ([1 parsec = about 3.26 light years, 19.174×10^{12} miles [30.857×10^{12} km]; mega parsec = 1 million parsecs, or 3,262,000 light years, or 2×10^{19} miles) is roughly homogenous.

Cosmology is based on a foundation of some observationally and theoretically supported assumptions about the structure of the universe. The cosmological principle states that the large-scale structure of the universe is homogenous and isotropic, meaning that at large scales the distribution of mass is the same in all parts of the universe, and that the universe looks the same in all directions of observation. The cosmological principle has important implications. For instance, the concept of homogeneity means that there is no edge to the universe, and the idea of isotropy means that there is no center of the universe. This seems to be confirmed by the observation that all galaxies in the universe can be measured to be rushing away from our galaxy, and that all galaxies appear to be moving relatively away from one another, in an expanding universe.

Accepting the cosmological principle of an isotropic and homogenous infinite universe leads to problems with basic observations from Earth. If the universe is infinite, homogenous, and isotropic, then a line of sight in any direction from Earth (or anywhere else) should eventually intersect with a star, and therefore there should be stars visible in all places in the sky, and the sky should be uniformly bright at night. The fact that the sky is mostly dark is known as Olber's paradox, after the German astronomer Heinrich Olber, who popularized this idea in the 19th century.

How can one reconcile Olber's paradox with the cosmological principle and with the observations of an expanding universe? Hubble's law (formulated by two American astronomers from the Midwest, Edwin Hubble [1889–1953] and Milton Humason [1891–1972] in 1929) states that the redshift of light coming from distant galaxies is proportional to their distance. This can be expressed as follows:

$$\text{recession velocity} = H_0 \times \text{distance}$$

where H_0 is Hubble's constant, which is equal to 46.5 miles (75 km)/sec/Megaparsec. Hubble's law can be used to estimate the age of the universe. Since the rate of recession of different galaxies from one another is known, and the recession rate increases with increasing distance, the time backward since the galaxies were all together in one place can be calculated. Since the rate increases with increasing distance, this number turns out to be the same regardless of which galaxies are used, and the date at which all galaxies were together turns out to be roughly 13 billion years ago. At that time everything in the universe, all matter, radiation, dark matter, dark energy—everything—was confined to a singular point, and from that instant exploded outward in a massive primordial expansion known as the big bang. One must remember, however, that the rate of expansion is assumed to be constant in this calculation, and most models for the universe suggest that the initial expansion may have been faster than that at present, which would make the true age of the universe younger than these estimates.

The concept of the big bang, where the universe started at a point and has been expanding with a certain velocity since then, implies that the universe is finite. This idea seems at odds with the cosmological principle, stating that the universe is infinite. The reconciliation can be understood by realizing that in the night sky only a finite part of the universe is visible. The light that reaches Earth is only from the part of the universe that is fewer than 13 billion years old; light from more distant parts, both in time and in space, has not reached Earth yet. Further, the idea of the big bang seems to indicate that the universe is finite, and that light from more than 13 billion years ago does not exist. The paradox still exists.

To understand this paradox more deeply, it is necessary to consider the nature of the big bang. The big bang was not matter suddenly exploding into space, expanding from a point. The big bang instead was the sudden expansion of everything, including space itself. The only known explanation for these observations is that the big bang was the sudden creation and expansion of space into nothing, and the galaxies, and everything else in the universe, is just along for the ride, expanding and moving away from one another, as the space of the universe expands. Therefore although the galaxies are moving away from one another, they are not moving (except for the smaller, and internal motions) with respect to the fabric of space. The space is actually expanding at the same rate the galaxies are moving apart from one another. Understanding the universe this way makes it clear that the big bang did not happen “somewhere,” with galaxies exploding from a distant point into space, but instead, the big bang happened “everywhere”—before the big bang, the infinitesimally small point that space expanded from was the entire universe, and the big bang happened everywhere in the whole universe at the same instant. Since then all space and all points in the universe have been moving away from one another.

It is difficult for the human mind to comprehend what existed before the big bang. The big bang itself was a singularity, a moment when according to the laws of physics, all of the mass and energy and space of the universe had zero size, and infinite density and temperature. This idea is based on the laws of physics as deciphered for a finite universe, however, and these laws do not apply to states such as singularities. The big bang represents the start of space, the beginning of mass, and the start of time. Therefore there is no concept such as what there was before the big bang, since before the time of the big bang, there was no time, there was no “before.”

The best descriptions of what the universe may have looked liked, and how it behaved, in the instant of the big bang are found in Einstein’s general theory of relativity, where the presence of extremely dense mass warps the space and time around it—and conversely, the curvature of space dictates how matter moves through that space. This leads to a different interpretation of the redshifts and inferred increasing velocity of distant galaxies as the distance between them increases. According to Hubble’s law, described above, this is due to the increasing relative velocities with increasing distance. Now according to Einstein’s general theory of relativity, it is necessary to think of this not as an increase in velocity, but instead as an expansion of the space in the universe. As the space through which the light is traveling expands, the wavelengths of the photons of light are influenced by this expansion, and they shift to longer wavelengths, causing the redshift. The amount of the redshift therefore corresponds to how much the universe has expanded since the photon was emitted—the further the photon came from, the more the expansion and the greater the redshift. The redshift really measures how much the universe has expanded since the photon was emitted, not the relative velocity of the distant galaxy from the observer. For most situations, however, the more familiar Newtonian laws of motion work quite well for objects and forces in the universe.

The shape of the universe depends on how much mass the universe contains, according to these relativistic concepts. Since mass warps space and time, the amount of mass in the universe actually determines the geometry of space itself. If the mass is above a critical value, then the space in the universe is curved back on itself and is said to be a closed universe, with a positive curvature—much like the inside of a sphere. In this kind of space, anything that moves in a straight line could theoretically end up back at the same position it started from, much like a small ball rolling inside a larger sphere. If the mass is less than the critical value, the shape of space is said to be open and has a negative curvature—much like the shape of a saddle. The third possibility is of a flat universe, where the density is exactly equal to the critical value.

COSMOLOGICAL MODELS FOR THE EVOLUTION OF THE UNIVERSE

Observations on the current state of the universe such as the relative velocities of galaxies show that it is expanding. A range of models suggests different fates for the universe from this point. Some models suggest that the universe will continue to expand forever, some that it will slow down and eventually collapse back on itself, perhaps repeating expansion/contraction cycles many times. Still other models suggest that the universe will reach a steady state, with the expansion slowing until it just stops. The factor deciding which of these models will occur depends primarily on how much mass is present in the universe. With a sufficient quantity, gravity may take over and cause the universe to collapse eventually; if the universe contains too little mass, then the expansion can continue indefinitely. A thin critical mass in between would suggest a steady-state universe that would eventually slow its expansion, attaining a steady state. The amount of matter per volume of space it takes to determine the difference among these different possible scenarios depends on the rate of expansion and is known as the critical density.

The future of the universe is vitally dependent on this critical density. If the density of matter is above the critical value, then the gravitational attraction will be enough to halt the expansion, and gravity would start to pull all the matter of the universe back inward, with all points moving toward one another as space contracted just in the opposite way from when it was expanding. This would take precisely the same amount of time that it took for the universe to expand, and everything would happen in reverse. Observers would see that nearby galaxies were blueshifted—but distant galaxies could still show redshifts, since the time it takes for the light to reach the observer could be greater than the time since the contraction started.

As the universe and space itself contract in this model, the frequency of collisions between galaxies increases, and the whole universe heats up and becomes denser. The process continues until the temperature is so high the whole universe is hotter than typical stars, and the contraction will continue to the point of a superhot, superdense, supersmall singularity, very similar or identical to that from which the universe first expanded. At this point the normal laws of physics break down again, and understanding the meaning of the universe that has no space and no time and infinite mass is beyond comprehension. Nonetheless, many cosmologists speculate that at this point the universe may suddenly go through another big bang and expansion phase, and that the universe may experience an infinite number of expansions and contractions, in an oscillating or bouncing universe model.

If the density of the universe is below the critical value, then its fate and future will be dramatically different. A universe with a density below the critical value will expand forever, and the radiation and light received from distant galaxies will eventually fade and disappear. Eventually even the light from the stars in the local Milky Way would disappear as they use up their fuel and go dark. The fate of this universe is a cold, dark death. At present it is difficult to tell which of these models may be closer to the real fate of the universe, but the critical measurement is being able to tell the true density of the universe.

Determining the density of the universe is not a simple task, since only about 4 percent of matter in the universe is visible and about 22 percent is dark matter, and about 74 percent of the rest of the universe is estimated to be dark energy. When astronomers calculate the density of the universe, using all the matter that they can see, the density of this luminous matter comes to about 10–28 kg/m^3, or about 1 percent of the mass needed to be the critical mass of the universe. Even if we include the present estimates for the dark matter in the universe, however, most models for the density suggest that the universe has only 20–30 percent of the mass of the critical density, implying that the universe will expand forever, and not retract upon itself.

Large uncertainties about the amount of dark matter in the voids in space and on very large scales may cause the amount of mass in the universe to be grossly underestimated. Some estimates of the amount of dark matter in these areas place the density of the universe very close to the critical value, so the present limits of detection cannot tell the future of the universe, or whether the future is dark and cold, or bright and very hot.

See also ASTRONOMY; ASTROPHYSICS; DARK MATTER; GALAXIES; ORIGIN AND EVOLUTION OF THE UNIVERSE; UNIVERSE.

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craton Cratons are large areas of relatively thick continental crust that have been stable for long periods of geological time, generally since the Archean. Most cratons are characterized by low heat flow and few or no earthquakes, and many have a thick mantle root or tectosphere that is relatively cold and refractory, having had a basaltic melt extracted from it during the Archean.

Understanding the origin of stable continental cratons hinges on recognizing which processes change the volume and composition of continental crust with time, and how and when juvenile crust evolved into stable continental crust. The evidence from the preserved record suggests that the continental landmass has been growing since the early Archean, although the relative rates and mechanisms of crustal recycling and crustal growth are not well known and have been the focus of considerable geological debate. The oldest rocks known on the planet are the circa 4.0-Ga Acasta gneisses from the Anton terrane of the Slave Province. The Acasta gneisses are chemically evolved and show trace and REE patterns similar to rocks formed in modern suprasubduction zone settings. Furthermore, the 3.8-billion-year-old Isua sequence from Greenland, the oldest known sedimentary sequence, is an accretionary complex. A few circa 4.2-Ga zircon grains have been found, but it is not clear whether these were ever parts of large continental landmasses. Approximately half of the present mass of continental crust was extracted from the mantle during the Archean.

Exposed portions of Archean cratons are broadly divisible into two main categories. The first are the "granite-greenstone" terranes, containing variably deformed assemblages of mafic volcanic/plutonic rocks, metasedimentary sequences, remnants of older quartzo-feldspathic gneissic rocks, and abundant late granitoids. The second main class of preserved Archean lithosphere is found in the high-grade quartzo-feldspathic gneiss terranes. Relatively little deformed and metamorphosed cratonic cover sequences are found over and within both types of Archean terrain, but they are especially abundant on southern Africa's Kaapvaal craton. Also included in this category are some thick and laterally extensive carbonate platforms similar in aspect to Phanerozoic carbonate platforms, indicating that parts of the Archean lithosphere were stable, thermally subsiding platforms.

Although the rate of continental growth is a matter of geological debate, most geological data indicate that the continental crust has grown by accretionary and magmatic processes taking place at convergent plate boundaries since the early Archean. Arclike trace element characteristics of continental crust suggest that subduction zone magmatism has played an important role generating the continental crust. Convergent margin accretionary processes that contribute to the growth of the continental crust can be divided into five major groups: (1) oceanic plateau accretion, (2) oceanic island arc accretion, (3) normal ocean crust (midocean ridge) accretion/ophiolite obduction, (4) back arc basin accretion, and (5) arc-trench migration/Turkic-type orogeny accretion. These early accretionary processes are typically followed by intrusion of late-stage anatectic granites, late gravitational collapse, and late strike-slip faulting. Together these processes release volatiles from the lower crust and mantle, and help to stabilize young accreted crust and form stable continents.

JUVENILE ISLAND ARC ACCRETION

Many Archean granite-greenstone terranes are interpreted as juvenile island arc sequences that grew above subduction zones and later amalgamated during collisional orogenesis to form new continental crust. The island arc model for the origin of the continental crust is supported by geochemical studies that show the crust has a bulk composition similar to arcs. Island arcs are extremely complex systems that may exhibit episodes of distinctly different tectonics, including accretion of ophiolite fragments, oceanic plateaux, and intra-arc extension with formation and preservation of back arc and intra-arc basins. Many juvenile arcs evolve into mature island arcs in which the magmatic front has migrated through its own accretionary wedge, and many evolve into continental margin arcs after they collide with other crustal fragments or continental nuclei.

Although accretion of immature oceanic arcs appears to have been a major mechanism of crustal growth in Archean orogens, some people argue that oceanic arc accretion alone is insufficient to account for the rapid crustal growth in Precambrian shields. Furthermore, most oceanic arcs are characterized by mafic composition, whereas the continental crust is andesitic.

OPHIOLITE ACCRETION

Ophiolites are a distinctive association of allochthonous rocks interpreted to form in a variety of plate tectonic settings such as oceanic spreading centers, back arc basins, forearcs, arcs, and other extensional magmatic settings including those in association with plumes. A complete ophiolite grades downward from pelagic sediments into a mafic volcanic complex generally made of mostly pillow basalts, underlain by a sheeted dike complex. These are underlain by gabbros exhibiting cumulus textures, then tectonized peridotite, resting above a thrust fault that marks the contact with underlying rock sequences. The term *ophiolite* refers to this distinctive rock association and should not be used in a purely genetic way to refer to allochthonous oceanic lithosphere rocks formed at midocean ridges.

Very few complete Phanerozoic-like ophiolite sequences have been recognized in Archean greenstone belts. However, the original definition of ophiolites includes "dismembered," "partial," and "metamorphosed" varieties, and many Archean greenstone belts contain two or more parts of the full ophiolite sequence. Archean oceanic crust was possibly thicker than Proterozoic and Phanerozoic counterparts, and this resulted in accretion predominantly of the upper section (basaltic) of oceanic crust. The thickness of Archean oceanic crust may in fact have resembled modern oceanic plateaux. If this were the case complete Phanerozoic-like, midocean ridge basalt (MORB)–type ophiolite sequences would have been very unlikely to be accreted or obducted during Archean orogenies. In contrast, only the upper, pillow lava–dominated sections would likely be accreted.

Portions of several Archean greenstone belts have been interpreted to contain dismembered or partial ophiolites. Accretion of MORB-type ophiolites has been proposed as a mechanism of continental growth in a number of Archean, Proterozoic, and Phanerozoic orogens. Several suspected Archean ophiolites have been particularly well documented. One of the most disputed is the circa 3.5-Ga Jamestown ophiolite in the Barberton greenstone belt of the Kaapvaal craton of southern Africa. The Jamestown sequence contains a 1.8-mile (3-km) thick sequence including a basal peridotite tectonite unit with chemical and textural affinities to Alpine-type peridotites, overlain by an intrusive-extrusive igneous sequence, and

DIAMONDS ARE FOREVER

Diamonds are the most precious of all stones, adorning many engagement rings, necklaces, and other jewelry. They are admired for their hardness, clarity, beauty, and ability to divide light into its component colors. Diamonds, it is said, are forever. Diamonds are stable crystalline forms of pure carbon that form only at high pressures in cool locations in the Earth's mantle. Their origin is restricted, therefore, to places in the subcontinental mantle where these conditions exist, between 90 and 125 miles (150–200 km) below the surface. The vast majority of diamonds that make their way back to the surface are brought up from these great depths by rare and strange explosive volcanic eruptions known as kimberlites.

Kimberlites and related rocks found in diatremes are rare types of continental volcanic rock, produced by generally explosive volcanism with an origin deep within the mantle. They form pipelike bodies extending vertically downward and are the source of most of the world's diamonds. Kimberlites were first discovered in South Africa during diamond exploration and mining in 1869, when the source of many alluvial diamonds on the Vaal, Orange, and Riet Rivers was found to be circular mud "pans," later appreciated to be kimberlite pipes. In 1871 two diamond-rich kimberlite pipes were discovered on the Vooruitzigt Farm in South Africa, owned by Nicolas de Beer. These discoveries led to the establishment of several large mines and one of the most influential mining companies in history.

Kimberlites are complex volcanic rocks with mixtures of material derived from the upper mantle and water-rich magma of several different varieties. A range of intrusive volcanic styles, including some extremely explosive events, characterizes kimberlites. True volcanic lavas are only rarely associated with kimberlites, so volcanic styles of typical volcanoes are not typical of kimberlites. Most near-surface kimberlite rocks are pyroclastic deposits formed by explosive volcanism filling vertical pipes, and they are surrounded by rings of volcanic tuff and related features. The pipes are typically a couple hundred yards wide, with the tuff ring extending another hundred yards or so beyond the pipes. The uppermost part of many kimberlite pipes includes reworked pyroclastic rocks, deposited in lakes that filled the kimberlite pipes after the explosive volcanism blasted much of the kimberlite material out of the hole. Geologic studies of kimberlites have suggested that they intrude the crust suddenly and behave differently from typical volcanoes. Kimberlites intrude violently and catastrophically, with the initial formation of a pipe filled with brecciated material from the mantle, sometimes including diamonds, reflecting the sudden and explosive character of the eruption. As the eruption wanes, a series of tuffs fall out of the eruption column, forming the tuff ring around the pipes. Unlike most volcanoes, kimberlite eruptions are not followed by the intrusion of magma into the pipes. The pipes simply get eroded by near-surface processes, lakes form in the pipes, and nature tries to hide the very occurrence of the explosive event.

Below these upward-expanding craters are deep vertical pipes known as diatremes that extend down into the mantle source region of the kimberlites. Many diatremes have features that suggest the brecciated mantle and crustal rocks were emplaced at low temperature capped by a chert-shale sequence. This partial ophiolite is pervasively hydrothermally altered and shows chemical evidence for interaction with seawater with high heat and fluid fluxes. Silicon dioxide (SiO_2) and magnesium dioxide (MgO) alteration and black smokerlike mineralization is common, with some hydrothermal vents traceable into banded iron formations and subaerial mudpool structures. These features led Maarten de Wit and others in 1992 to suggest that this ophiolite formed in a shallow sea and was locally subaerial, analogous to the Reykjanges ridge of Iceland. In this sense Archean oceanic lithosphere may have looked very much like younger oceanic plateaux lithosphere.

Several partial or dismembered ophiolites have been described from the Slave Province of northern Canada. A fault-bounded sequence on Point Lake grades downward from shales and chemical sediments (umbers) into several kilometers of pillow lavas intruded by dikes and sills, locally into multiple dike/sill complexes, then into isotropic and cumulate-textured layered gabbro. The base of this partial Archean ophiolite is marked by a 3,000-foot (1-km) thick shear zone composed predominantly of mafic and ultramafic mylonites, with less deformed domains including dunite, websterite, wherlite, serpentinite, and anorthosite. Syn-orogenic conglomerates and sandstones were deposited in several small foredeep basins, and are interbedded with mugearitic lavas (and associated dikes), all deposited/intruded in a foreland basin setting.

A complete but dismembered and metamorphosed 2.5-billion-year-old ophiolite complex from the North China craton has been described. This

nonviolently, presenting a great puzzle to geologists. How can a deep source of broken mantle rocks passively move up a vertical pipe to the surface, suddenly explode violently, then disappear beneath a newly formed lake?

Early speculations on the intrusion and surface explosion of the diamond-containing kimberlites suggested that they rose explosively and catastrophically from an origin in the mantle. Subsequent studies revealed that the early deep parts of their ascent did not seem to be explosive. It is likely that kimberlite magma rises from deep in the upper mantle along a series of cracks and fissures until it gets to shallow levels, where it mixes with water and becomes extremely explosive. Other diatremes may be more explosive from greater depths, and they may move as gas-filled bodies rising from the upper mantle. As the gases move into lower-pressure areas, they would expand and the kimberlite would move faster until it explodes at the surface. Still other ideas for the emplacement of kimberlites and diatremes invoke hydrovolcanism, or the interaction of the deep magma with near-surface water. Magma may rise slowly from depth until it encounters groundwater in fractures or other voids, leading to an explosion when the water mixes with the magma. The resulting explosion could produce the volcanic features and upward-expanding pipe found in many kimberlites, spewing the kimberlite magma and diamonds across a wide area on the surface.

It is likely that some or all of the processes discussed here play a role in the intrusion of kimberlites and diatremes, the important consequence being a sudden, explosive volcanic eruption at the surface, far from typical locations of volcanism, and the relatively rapid removal of signs of this volcanism. The initial explosions are likely to be so powerful that they may blast material into the stratosphere, though other kimberlite eruptions may form only small eruptions and ash clouds.

Diamonds are the hardest substance known and are widely used as gemstones. Uncut varieties may show many different crystal shapes, and many show striated crystal faces. They crystallize in isometric tetrahedral forms, exhibit concoidal fracture, have a greasy luster, and may be clear, yellow, red, orange, green, blue, brown, or even black. Triangular depressions are common on some crystals, and others may be preserved as elongate or pear-shaped forms. Diamonds have been found in alluvial deposits such as gravel, and some mines have been located by tracing the source of the gravel to the kimberlite pipe from where the diamonds were brought back to the surface. Some diamond-mining operations such as those of the Vaal River, South Africa, proceeded for many years before it was recognized that the source was in nearby kimberlites.

Dating the age of formation of small mineral inclusions in diamonds has yielded important results. All diamonds from the mantle appear to be Precambrian, with one type being up to 3.2 billion years old, and another 1.0 to 1.6 billion years old. Since diamonds form at high pressures and low temperatures, their very existence shows that the temperature deep in the Earth beneath the continents in the Precambrian was not much hotter than today. The diamonds were stored deep beneath the continents for billions of years before being erupted in the kimberlite pipes. Diamonds really are forever.

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ophiolite has structurally disrupted (faulted) pillow lavas, mafic flows, breccia, and chert overlying a mixed dike and gabbro section that grades down into layered gabbro, cumulate ultramafics, and mantle peridotites. High-temperature mantle fabrics and ophiolitic mantle podiform chromitites have also been documented from the Dongwanzi ophiolite, and it has ophiolitic mélange intruded by arc magmas.

Dismembered ophiolites appear to be a widespread component of greenstone belts in Archean cratons, and many of these apparently formed as the upper parts of Archean oceanic crust. Most of these are interpreted to have been accreted within forearc and intra-arc tectonic settings. The observation that Archean greenstone belts have such an abundance of accreted ophiolitic fragments compared to Phanerozoic orogens suggests that thick, relatively buoyant, young Archean oceanic lithosphere may have had a rheological structure favoring delamination of the uppermost parts during subduction and collisional events.

OCEANIC PLATEAUX ACCRETION

Oceanic plateaux are thicker than normal oceanic crust formed at midocean ridges; they are more buoyant and relatively unsubductable, forming potential sources of accreted oceanic material to the continental crust at convergent plate boundaries. Accretion of oceanic plateaux has been proposed as a mechanism of crustal growth in a number of orogenic belts, including Archean, Proterozoic, and Phanerozoic examples. Oceanic plateaux are interpreted to form from plumes or plume heads that come from the lower mantle (D″) or the 415-mile (670-km) discontinuity, and they may occur either within the interior of plates or interact with the upper mantle convective/magmatic system and occur along midocean ridges. Oceanic plateaux may be sites of komatiite formation preserved in Phanerozoic through Archean mountain belts, based on a correlation of allochthonous komatiites and high-MgO lavas of Gorgona Island, Curaçao, and the Romeral fault zone, with the Cretaceous Caribbean oceanic plateau.

Portions of several komatiite-bearing Archean greenstone belts have been interpreted as pieces of dismembered Archean oceanic plateaux. For instance, parts of several greenstone belts in the southern Zimbabwe craton are allochthonous and show a similar magmatic sequence, including a lower komatiitic unit overlain by several kilometers of tholeiitic pillow basalts. These may represent a circa 2.7-Ga oceanic plateau dismembered during a collision between the passive margin sequence developed on the southern margin of the Zimbabwe craton and an exotic crustal fragment preserved south of the suturelike Umtali line.

The accretion of oceanic plateaux and normal oceanic crust in arc environments may cause a backstepping of the subduction zone. As the accretionary complex grows, it is overprinted by calc-alkaline magmatism as the arc migrates through the former subduction complex. Further magmatic and structural events can be caused by late-ridge subduction and strike-slip segmentation of the arc. Average geochemical compositions of the continental crust, however, are not consistent with ocean plateau accretion alone.

Parts of many Archean, Proterozoic, and Phanerozoic greenstone belts interpreted as oceanic plateau fragments are overprinted by arc magmatism, suggesting that they either formed the basement of intraoceanic island arcs or they have been intruded by arc magmas following their accretion. Perhaps the upper and lower continental crusts have grown through the accretion of oceanic island arcs and ocean plateaus, respectively. Accreted oceanic plateaux may form a significant component of the continental crust, although most are structurally disrupted and overprinted by arc magmatism.

BACK ARC BASIN ACCRETION

The formation, closure, and preservation of back arc basin sequences has proven to be a popular model for the evolution of some greenstone belts. Paradoxically, the dominance of buoyant subduction styles in the Archean should have led to dominantly compressional arc systems, but many workers suggest back arc basins (which form in extensional arcs) as a modern analog for Archean greenstone belts.

ARC-TRENCH MIGRATION AND ACCRETIONARY OROGENS; A PARADIGM FOR THE ARCHEAN

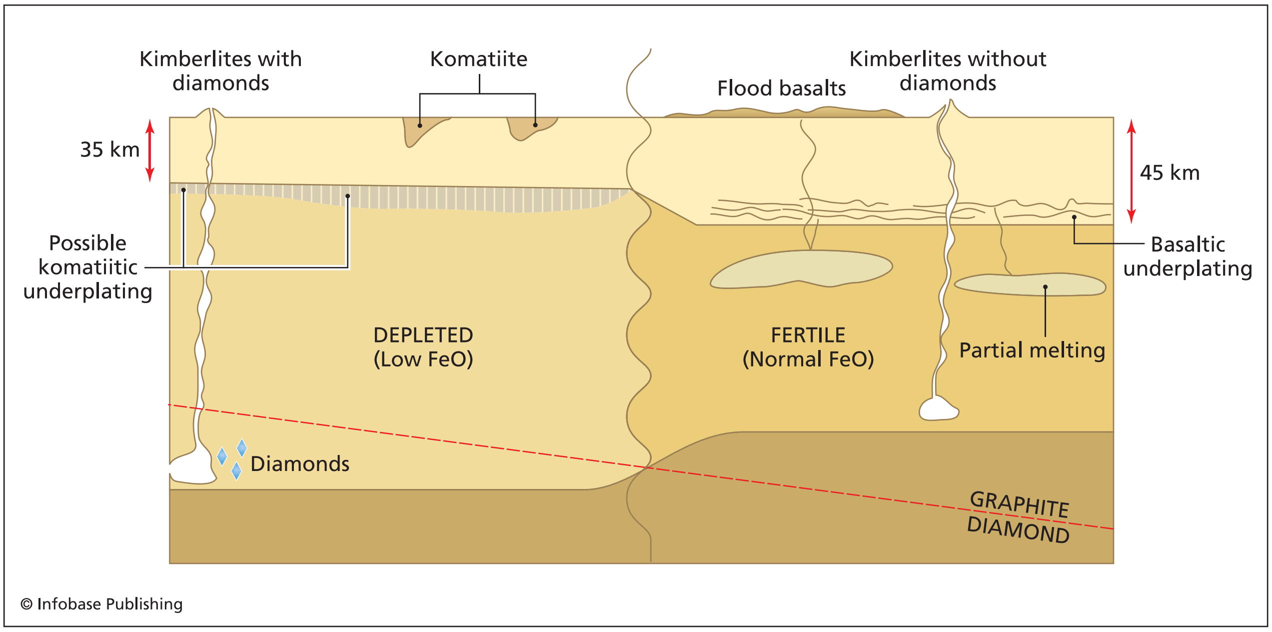
Turkic-type accretionary orogens are large, subcontinent-size accretionary complexes built on one or two of the colliding continents before collision, through which magmatic arc axes have migrated, and are later displaced by strike-slip faulting. These accretionary wedges are typically built of belts of flysch, disrupted flysch and mélange, and accreted ophiolites, plateaux, and juvenile island arcs. In 1996 A. M. Celal Sengör and Boris Natal'n reviewed the geology of several Phanerozoic and Precambrian orogens and concluded that Turkic or accretionary-type orogeny is one of the principal builders of continental crust with time. The record of Archean granite-greenstone terranes typically shows important early accretionary phases followed by intrusion by arc magmatism, possibly related to the migration of magmatic fronts through large accretionary complexes. In examples like the Superior Province, many subparallel belts of accreted material are located between continental fragments separated by many hundreds of miles, and thus may represent large accretionary complexes that formed prior to a "Turkic-type" collision. Late-stage strike-slip faulting is important in these Archean orogens, as in the Altaids and Nipponides, and may be partly responsible for the complexity and repetition of belts of similar character across these orogens.

Turkic or accretionary-type of orogeny provides a good paradigm for continental growth. These orogenic belts possess very large sutures (up to several hundred kilometers wide) characterized by subduction-accretion complexes and arc-derived granitoid intrusions, similar to the Circum-Pacific accreted terranes (e.g., Alaska, Japan). These subduction-accretion complexes are composed of tectonically juxtaposed fragments of island arcs, back arc basins, ocean islands/plateaux, trench turbidites, and microcontinents. Turkic or accretionary-type orogens may also experience late-stage extension associated with gravitational collapse of the orogen, especially in association with late collisional events that thicken the crust in the internal parts of the orogen. In the Archean slightly higher mantle temperatures may have reduced the possible height that mountains would have reached before the strength of deep-seated rocks was exceeded, so that extensional collapse would have occurred at crustal thickness lower than those of the younger geological record. Another important feature of these orogens is the common occurrence of orogen parallel strike-slip fault systems, which resulted in lateral stacking and bifurcating lithological domains. In these respects the accretionary-type orogeny may be considered as a unified accretionary model for the growth of the continental crust.

LATE-STAGE GRANITES AND CRATONIZATION

Archean cratons are ubiquitously intruded by late- to post-kinematic granitoid plutons, which may play a role in or be the result of some process that has led to the stabilization or "cratonization" of these terranes and their preservation as continental crust. Most cratons also have a thick mantle root or tectosphere, characterized by a refractory composition (depleted in a basaltic component), relatively cold temperatures, high flexural rigidity, and high shear wave velocities.

Outward growth and accretion in granite-greenstone terranes provides a framework for the successive underplating of the lower parts of depleted slabs of oceanic lithosphere, particularly if some of the upper sections of oceanic crust are offscraped and accreted, to be preserved as greenstone belts or eroded to form belts of greywacke turbidites. These underplated slabs of depleted oceanic lithosphere will be cold and compositionally buoyant compared with surrounding asthenosphere (providing that the basalt is offscraped and not subducted and converted to eclogite) and may contribute to the formation of cratonic roots. One of the major differences between Archean and younger accretionary orogens is that Archean subducted slabs were dominantly buoyant relative to the dense mantle, whereas younger slabs were not. This may be a result of the changing igneous stratigraphy of oceanic lithosphere, resulting from a reduction in heat flow with time,



Idealized cross section of craton, showing thick mantle root perhaps explaining why Archean cratons have thick roots and are relatively undeformable compared with their younger counterparts. Geometric aspects of underplating these slabs predict that they will trap suprasubduction mantle wedges of more fertile and hydrated mantle, from which later generations of basalt can be generated.

Many granites in Archean terranes appear to be associated with crustal thickening and anatexis during late stages of collision. However, some late-stage granitoids may directly result from decompressional melting associated with upper-crustal extensional collapse of Archean orogens thickened beyond their limit to support thick crustal sections, as determined by the strength of deep-seated rocks. Decompressional melting generates, from the trapped wedges of fertile mantle, basaltic melts that intrude and partially melt the lower crust. The melts assimilate lower crust, become more silicic in composition, and migrate upward to solidify in the mid to upper crust, as the late to postkinematic granitoid suite. In this model the tectosphere (or mantle root) becomes less dense (compositionally buoyant) and colder than surrounding asthenosphere, and this makes it a stable cratonic root that shields the crust from further deformation.

Late-stage strike-slip faults that cut many Archean cratons may also play an important role in craton stabilization. Specifically the steep shear zones may provide conduits for massive fluid remobilization and escape from the subcontinental lithospheric mantle, which would both stabilize the cratonic roots of the craton and initiate large-scale granite emplacement into the mid and upper crust.

See also ARCHEAN; GREENSTONE BELTS; OROGENY; PRECAMBRIAN.

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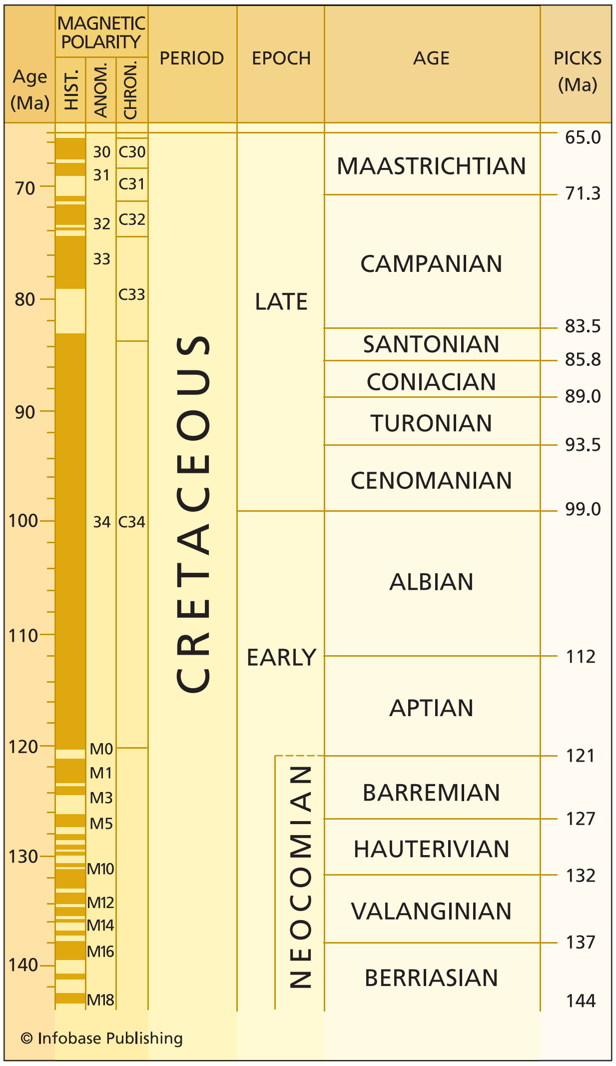
Cretaceous The youngest of three periods of the Mesozoic, during which rocks of the Cretaceous System were deposited, the Cretaceous ranges from 144 million years (Ma) ago until 66.4 Ma and is divided into the Early and Late Epochs and 12 ages. The name derives from the Latin *creta,* "chalk," in reference to the chalky terrain of England of this age.

Pangaea was dispersing during the Cretaceous, and the volume of ridges plus apparently the rate



Cretaceous timescale

Artwork of Cretaceous period scene, showing many dinosaur and other species, including pterosaurs, nautoloid mesosaur, pleisiosaur, hesperomis, belemnite, and other life-forms. *(Publiphoto/Photo Researchers, Inc.)*

of seafloor spreading were dramatically increased. The consequential displacement of seawater caused global sea levels to rise, so the Late Cretaceous was marked by high sea levels and the deposition of shallow water limestones in many epicontinental seas around the world. On the North American craton, the Zuni Sequence was deposited across wide parts of the craton during this transgression. Increased magmatic activity in the Cretaceous may reflect more rapid mantle convection or melting, as marked by a number of igneous events worldwide. The South American Cordillera and the western United States saw unusual amounts of intrusive and volcanic activity. The giant flood basalt provinces of Paraná in South America and the Deccan of India were formed, and kimberlite pipes punctured the lithosphere of South Africa and Greenland. The dispersal of Pangaea was associated with the opening of the Atlantic Ocean. Africa rotated counterclockwise away from South America, closing the Tethys Ocean in the process of opening the Atlantic. The closure of Tethys was associated with the emplacement of many ophiolites onto continents, including the giant Oman (Semail) ophiolite that was thrust to the south onto the Arabian continental margin.

Cretaceous sedimentary patterns suggest that the climate was warming through the period and was more varied and seasonal than in the earlier Mesozoic. The famous Cretaceous chalks were formed by the accumulation of tests of calcareous marine algae known as coccoliths, which thrived in the warm shallow seas. The chalks are in many places interbedded with fossiliferous limestones with abundant brachiopods and rudist coral fragments.

Life on the Cretaceous continents saw the development of the angiosperms, which became the planet's dominant flora by the middle of the period. Invertebrate and vertebrate animals were abundant and included many species of dinosaurs, giant flying pterosaurs, and giant marine reptiles. Dinosaurs occupied many different geological niches, and most continents have fossil dinosaurs, including herbivores, carnivores, and omnivores. Birds had appeared, both flying and swimming varieties. Mammals remained small, but their diversity increased. Many life-forms began a dramatic, progressive disappearance toward the end of the period. These marine and land extinctions seem to be a result of a combination of events including climate change and exhalations from the massive volcanism in the Indian Deccan and South American Paraná flood basalt provinces, coupled with an impact of a six-mile (10-km) wide meteorite that hit the Yucatán Peninsula of Mexico. The extinctions were not all abrupt—many of the dinosaur and other genera had gone extinct, probably from climate stresses, before the meteorite hit the Yucatán Peninsula. When the impact occurred, a 1,000-mile (1,600-km) wide fireball erupted into the upper atmosphere, and tsunami hundreds or thousands of feet (hundreds of meters) high washed across the Caribbean, southern North America, and much of the Atlantic. Huge earthquakes accompanied the explosion. The dust blown into the atmosphere immediately initiated a dark global winter, and as the dust settled months or years later, the extra carbon dioxide in the atmosphere warmed the Earth for many years, creating a greenhouse condition. Many forms of life could not tolerate these rapid changes and perished. The end Cretaceous extinction, commonly referred to as the K-T event, is one of the most significant mass extinction events known in the history of life.

See also CENOZOIC; MASS EXTINCTIONS; MESOZOIC.

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crust Thin, low-density rock material called crust makes up the outer layer of the solid Earth, ranging in thickness from about three miles (five km) and less near the midocean ridges, to more than 50 miles (70 km) beneath the tallest mountain ranges. This is followed inward by the mantle, a solid rocky layer extending to 1,802 miles (2,900 km). The outer core is a molten metallic layer extending to 3,169-mile (5,100-km) depth, and the inner core is a solid metallic layer extending to 3,958 miles (6,370 km).

The temperature increases with depth with a gradient of 30°C per kilometer (139°F per mile) in the crust and upper mantle, and with a much smaller gradient deeper within the Earth. The heat of the Earth comes from residual heat trapped from initial accretion, radioactive decay, latent heat of crystallization of outer core, and dissipation of tidal energy of the Sun-Earth-Moon system. Heat flows from the interior of the Earth toward the surface through convection cells in the outer core and mantle. The top of the mantle and the crust compose a relatively cold and rigid boundary layer, or lithosphere, which is about 65 miles (100 km) thick. Heat escapes through the lithosphere largely by conduction or transport in igneous melts, and in convection cells of water through midocean ridges.

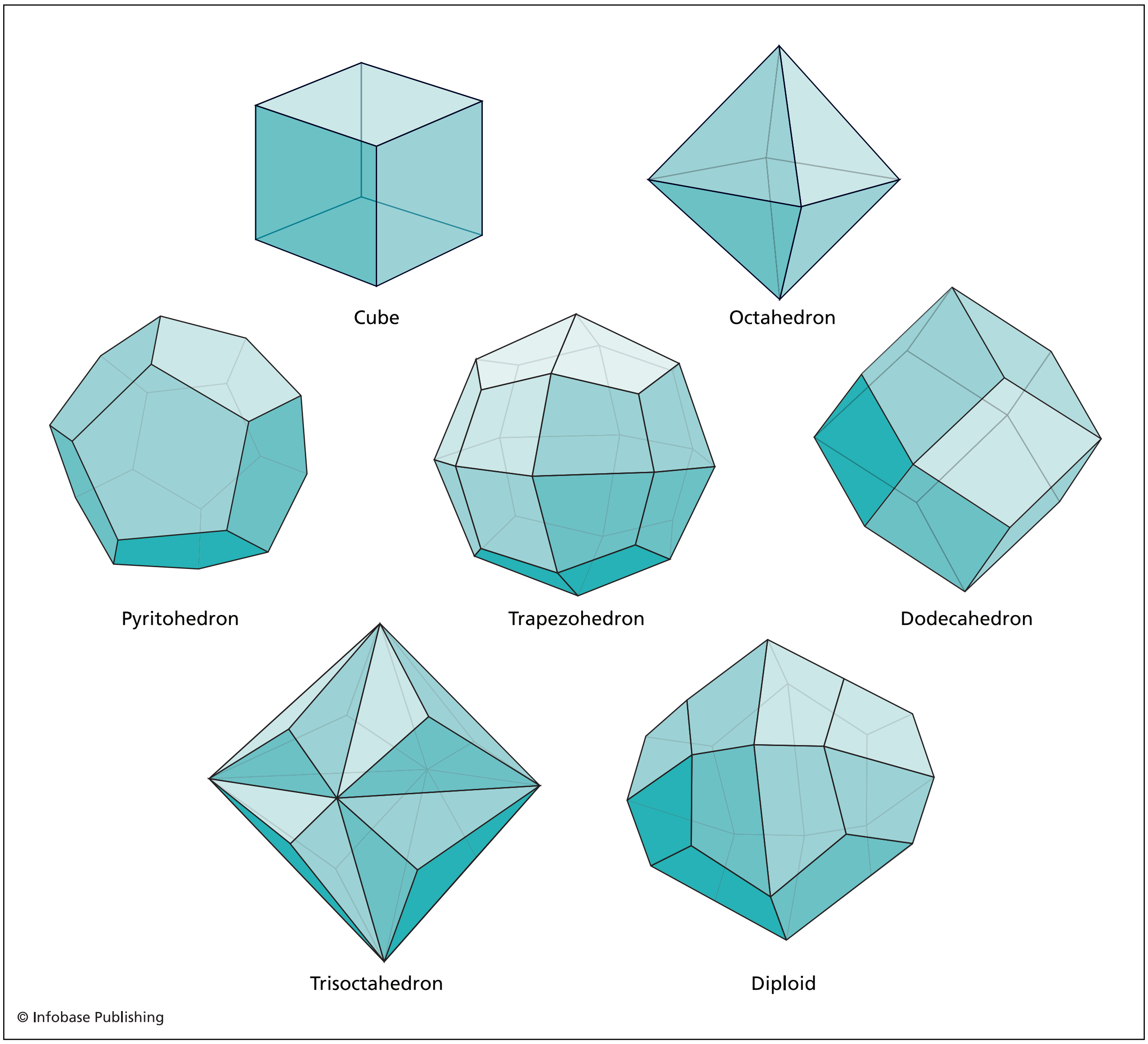
The Earth's crust is divisible broadly into continental crust of granodioritic composition and oceanic crust of basaltic composition. Continents make up 29.22 percent of surface, whereas continental crust underlies 34.7 percent of the Earth's surface, with continental crust under continental shelves accounting for the difference. The continents are in turn divided into orogens, made of linear belts of concentrated deformation, and cratons, making the stable, typically older interiors of the continents.

The distribution of surface elevation is strongly bimodal, as reflected in the hypsometric diagrams. Continental freeboard is the difference in elevation between the continents and ocean floor and results from difference in thickness and density between continental and oceanic crust, tectonic activity, erosion, sea level, and strength of continental rocks.

See also CONTINENTAL CRUST; CRATON; LITHOSPHERE; OCEAN BASIN.

crystal, crystal dislocations Crystals are homogeneous solid structures composed of chemical elements or compounds having a regularly repeating arrangement of atoms, as well as a large number of defects in the crystal lattice, such as dislocations. All minerals are solids, and in all minerals the atoms are arranged in a very regular geometric form that is unique to that mineral. Every mineral of that species has an identical crystalline structure. This regular structure gives each mineral its characteristic color, chemistry, hardness, and crystal form.

Many minerals may not have a well-developed external crystal form, but still must have a regularly repeating crystal lattice composed of the constituent atoms. Crystal forms and the internal atomic lattice exhibit symmetry, which may be of several different varieties. Crystals exhibit four main types of symmetry. In mirror plane symmetry, the simplest, the crystal can be divided by an imaginary mirror plane that would result in two halves that are mirror images of one another. Crystals may have symmetry about



The seven basic types of crystal forms

an axis that runs through the center of the crystal, in which the crystal lattice would be rotated into an identical configuration two, three, four, or six times in a 360° circuit. These symmetry systems are known as diads, triads, tetrads, and hexads. A more complex form of symmetry is known as roto inversion, characterized by a rotational operation followed by inversion of the lattice across its center point. Finally, a simple inversion across the center of the crystal leads to a crystal face diametrically opposite to every other crystal face. In various combinations of these symmetry operations, all crystals belong to one of seven crystal systems. These include cubic, tetragonal, orthorhombic, monoclinic, triclinic, hexagonal, and trigonal.

Crystals may appear to be close to perfect, but they always have millions of atomic defects. These include vacancies in the crystal lattice, various types of defects in the arrangement of the atoms and lattice, and replacements of one type of atom or ion by another with a similar charge and size.

CRYSTAL DISLOCATIONS AND OTHER CRYSTAL DEFECTS

Crystals are regularly ordered symmetrical arrays of atoms, but like anything else in nature they are not perfect and have many defects. Some defects are acquired during growth of the crystals when they first form, and others develop in the crystals during deformation. These defects determine the strength of crystals, minerals, and rocks. The motion of these defects accommodates the strain of crystals.

The motion of crystal defects is an important deformation mechanism, with different types of motion of different types of defects operating at different temperatures, pressures, and applied stresses. There are two main types of crystal defects: point defects and line defects. Point defects include vacancies, impurities, and interstitials, whereas line defects are known as dislocations.

Point defects are considered irregularities, or defects, that affect one point in a crystal lattice. Several types include impurities, in which the wrong type of atom is present in the crystal lattice in the place of another; vacancies, in which an atom is missing from the atomic lattice; and interstitials, in which an atom occupies a site that is not normally occupied. Other types of point defects are more complex and involve more than one atom at a time.

In a regularly ordered crystal lattice most electric charges are satisfied by bonding and balancing positive and negative charges. Crystals having point or other defects have more internal energy because many bonds are broken or unsatisfied and the electric charges are not neutralized. Crystals are more apt to react or deform when they have a higher internal energy. Temperature causes the number of vacancies to increase, whereas pressure causes the number of vacancies to decrease.

Cubic crystal of fluorite, about two inches (5 cm) on each face, on quartz with barite from Frazer's Hush Mine, Weardale, England *(Mark A. Schneider/Photo Researchers, Inc.)*

When a crystal is stressed, vacancies tend to move, or diffuse, in an orderly manner related to the stress field, migrating toward the crystal face with the highest stress, whereas atoms tend to migrate in the opposite direction toward the crystal faces with the lowest stress. This process of migration of vacancies is called Nabarro-Herring creep. This kind of diffusion can accommodate a general shape change of a crystal, such as occurs during regional deformation in many mountain belts worldwide.

Twinning, the misorientation of a crystallographic plane across a plane in the crystal lattice, can be caused by mismatched growth or by deformation. Mechanical or stress-induced twinning differs from growth twinning in that shear across a crystal plane changes the lattice orientation. The shear occurs across a crystal plane, which must be a symmetry plane of the crystal. The amount of strain is limited by the crystallographic relationship for each type of crystal, though it typically falls in the range of 20°–45°.

Translation gliding is a deformation mechanism in crystals whereby the crystal lattice structure slips along some internal crystallographic plane, after some critical value of shear stress is reached. Slip, or translation gliding, usually occurs in very specific crystallographic directions in crystals called slip systems, favoring directions that

- have short distances between equivalent atoms
- occur in directions that do not juxtapose ions of like charge.

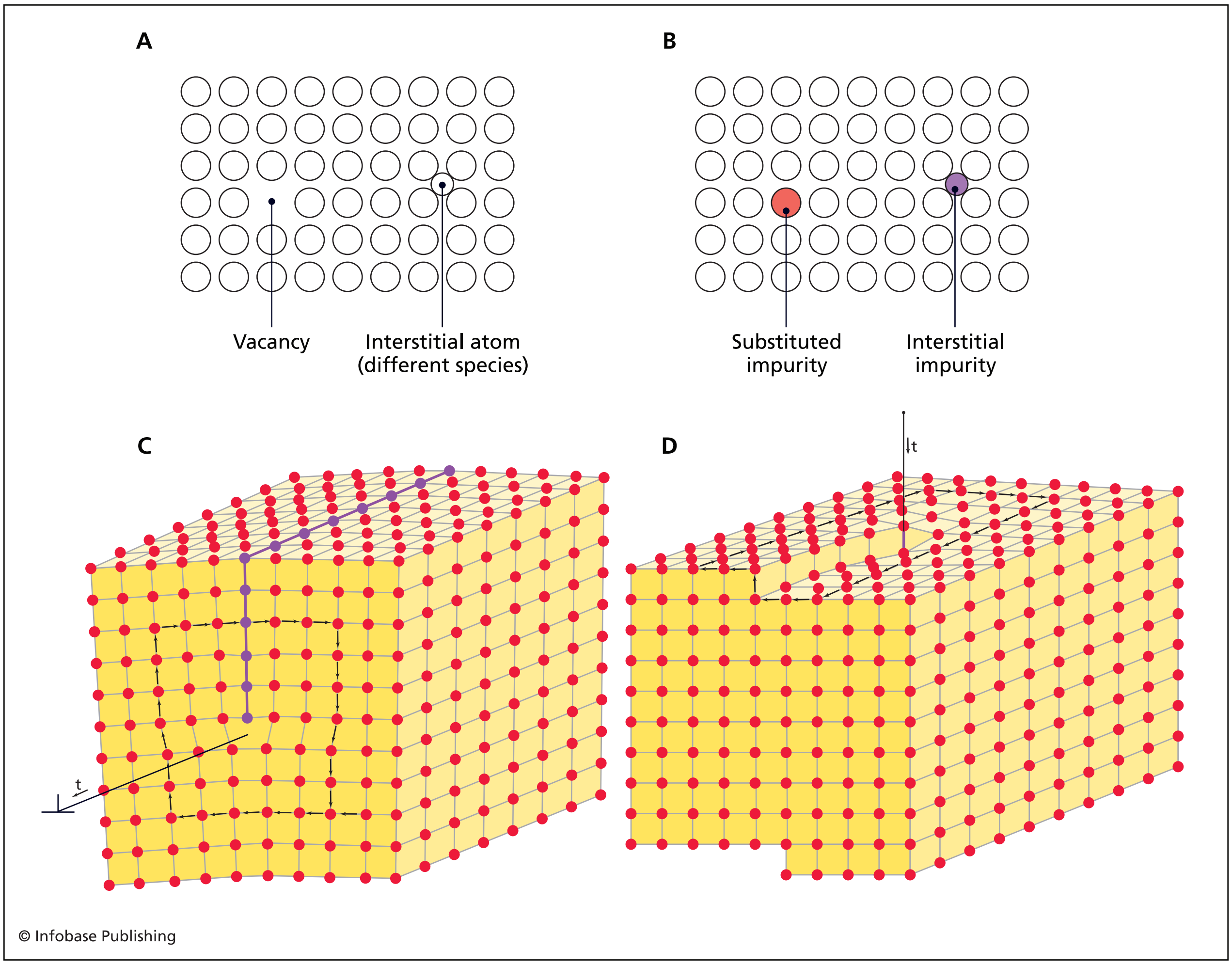
Slip on these crystallographic directions begins when the critical resolved shear stress for that crystallographic direction is surpassed.

Most crystals have many slip systems activated at different critical resolved shear stresses, so slip begins on the planes with the lowest critical resolved shear stress. Soon different slip systems start to interfere with each other and deformation will either stop or the stress will rise to enable continued deformation. This increase in stress is known as work hardening.

Crystals need to have five independent slip systems to accommodate any general homogenous strain. If the crystal has fewer than five, it will eventually crack or fracture. Different slip systems may be activated at different temperatures, or strain rates, so the relationships of which slip systems are active under different deformation conditions are complex.

Dislocations are best thought of as an extra plane of atoms that terminates somewhere in the crystal lattice. They are often referred to as an extra half-plane because of this geometry. The presence of dislocations weakens the crystal structure. Their motion accounts for much of the strain in crystals. Dislocations move through a crystal lattice much like a ridge can be moved across a carpet, slowly moving the carpet across a floor without moving the whole carpet at one time. The stress required to break one bond at a time to move a dislocation from one place to another in a crystal lattice is much less than breaking all the bonds along a specific crystallographic direction simultaneously.

There are two basic types of dislocations: edge dislocations and screw dislocations. Edge dislocations are simpler, and are basically an extra half-plane of atoms that extends partway across the crystal lattice structure. Screw dislocations, however, are more complex, and have a twisted shape that resembles a parking garage, where one layer of the lattice is offset by a twisted, coil-like motion about an axis perpendicular to the planes. Most dislocations in crystals have both edge and screw components and form complex geometrical shapes.



Types of point and line defects in crystals, including vacancies, interstitials, edge dislocation, and screw dislocation

Dislocations form loops within crystals, marking boundaries between slipped and unslipped portions. This type of motion and slipping in crystals is exactly analogous to motions on faults.

Interactions of Dislocations

During deformation there are so many dislocations moving around in a crystal that they are bound to interact in several ways. Dislocation annihilation occurs when two dislocations of opposite signs move toward each other on the same slip plane and their extra half planes meet and form a complete crystal lattice, effectively canceling each other out of existence. Each dislocation in a crystal induces a stress field known as the self-stress field, since they disrupt the normal crystallographic structure. These stress fields interact for large distances within the crystals, causing either repulsions or attractions between dislocations, much as magnets repel or attract each other depending on charge. In the case of dislocations, however, attractions are deadly because if two dislocations are on the same slip plane and are attracted, they come together and annihilate each other. If they repel each other, the number of dislocations increases and higher and higher stresses are needed to make the dislocations move as the number of repelled dislocations increases during deformation.

Dislocations often encounter immobile, tightly bounded impurities, such as interstitials, which pin dislocations behind them. As more dislocations move toward the region with the impurities, they too become stuck and are repelled by each other's stress fields. This causes dislocation pile-ups. Dislocations can also interact with other dislocations, also causing pile-ups.

When the temperature of the deforming crystal is high, vacancies can diffuse toward the obstacle, or atoms can move away from the half-plane, enabling dislocations to climb over obstacles. Thus there are two main mechanisms by which dislocations move through crystals: gliding and climbing.

When dislocations of different slips systems move through each other, they offset the other slip plane, forming a dislocation jog, which is basically a step in the slip system that one of the dislocations moved along. Once there is a jog in the slip plane, it becomes more difficult for dislocations to move along that slip plane, and they must climb over the jog to progress. Dislocation jogs can be made to disappear, or evaporate, by diffusion of vacancies toward them or movement of atoms away from the jog.

Work hardening is any process that makes increased deformation harder, requiring more stress to do the same amount of deformation. Work hardening can occur by

- formation of dislocation jogs
- dislocation pile-ups
- interaction of stress fields
- increase in dislocation density

Work hardening is more common at low temperatures, as high temperatures cause increased diffusion of vacancies and climb to occur.

Annealing is any process that tends to return a crystal lattice to a less deformed state, such as through a reduction in the number of dislocations. A lattice with fewer dislocations has lower energy and is more stable that one with a high dislocation density. There are several different common ways that a crystal anneals:

- group dislocations in a more stable configuration
- migration of dislocations to an edge of crystal
- recrystallization of grains

Diffusion helps all of these processes, so annealing is faster at high temperatures. Annealing mechanisms are also diverse and include the following:

- Dislocations of opposite signs can climb to the same slip plane and annihilate each other.
- Dislocations can glide and climb to grain boundaries.
- Formation of subgrain boundaries by dislocation motion concentrates dislocations into planes, or walls that bound domains of low-dislocation density.
- Recrystallization, or regrowth, of the entire crystal lattice, with new grains having low-dislocation density. Often this process starts in regions of high-dislocation density or along grain boundaries. Prolonged heating leads to grain growth, and some grains grow at the expense of neighbors. Recrystallization forms grains that are equant, have 120° grain boundaries at triple junctions.

At temperatures lower than those where dislocation glide and climb operate, rocks flow by other mechanisms. Pressure solution, or grain boundary diffusion (also called Coble creep), is where crystals are flattened and dissolved along their edges. The extra dissolved material is either precipitated at the ends of the grains or moved away to be precipitated in veins or pores, or far away. This deformation mechanism can easily accommodate large bulk shortening and stretching. Pressure solution often produces seams, or stylolites, which are leftover concentrations of insoluble material from where the rock dissolved much of the other material. Stylolites are interesting because in three dimensions they form irregular surfaces with cones or teeth on them, pointed to the maximum compressive stress. Pressure solution works much like squeezing an ice cube. Grain-grain boundaries that are initially touching have the highest stresses on them and are the first to be dissolved.

Compaction is also an important deformation mechanism in sedimentary basins due to the weight of overlying rocks. Compaction often involves dewatering, or removal of fluids, from the pore spaces of a rock. The weight of newly deposited sediments and overlying rocks adds pressure and pushes the grain-to-grain contacts between crystals or grains closer together, expelling the fluids. Some muds begin with a porosity of 80 percent and end with 10 percent on burial. In these cases a large quantity of water is expelled from the system during compaction. Sandstones have initial porosities of up to 45 percent, reduced to about 10–30 percent depending on the rock, pressure, and fluid. Porosity decreases with increasing burial depth.

See also DEFORMATION OF ROCKS; MINERAL, MINERALOGY; STRUCTURAL GEOLOGY.

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D

Dana, James Dwight (1813–1895) American *Geologist, Mineralogist* James Dana was born on February 12, 1813, in Utica, New York, in a region surrounded by Paleozoic sedimentary rocks and Precambrian crystalline rocks of the Adirondack Mountains. His teacher at Utica High School, Fay Edgerton, noticed the young Dana's keen interest in science and helped him gain entrance to Yale College, where he received scientific training by Benjamin Silliman, the prominent scientist and founder of the *American Journal of Science*. In terms of enduring scientific achievement James Dwight Dana is one of Yale's most notable scientific figures. His contributions to geology, mineralogy, and zoology formed the basis of classification systems still in use today by scientists in these fields of study.

After Dana graduated from Yale in 1833, he became a mathematics teacher to midshipmen in the U.S. Navy and sailed to the Mediterranean from 1833 to 1835. Dana returned to Yale in 1836 and 1837 and worked as an assistant to Silliman, helping with chemistry laboratories. In 1836 Dana was invited to be a scientific participant of the United States Exploring Expedition, due to sail to the South Seas in 1838. Originally invited on the expedition as its geologist, he assumed the role of zoologist after the departure of James Couthouy in 1840. Dana produced two important monographs based on his study of animals collected during the exploring expedition. These monographs, one on corals and anemones and the other on crustaceans, were extraordinary for their sheer size, scope, and detail. Virtually no modern coral or crustacean researcher today can undertake significant systematic research without encountering by James Dana's legacy.

Dana returned to America in 1842 and spent the next 13 years writing reports from his four years at sea, including detailed reports of the geology and mineralogy of the Mount Shasta, California, area, a poorly studied region at the time. Dana returned to New Haven, Connecticut, and Yale University in 1844, where he married Silliman's daughter Henrietta. He then succeeded Silliman by taking the Silliman professorship of natural history and geology and stayed in that position until 1892.

James Dana is best known for his books on mineralogy, including his *System of Mineralogy,* (1837), *Manual of Mineralogy* (1848), and *Manual of Geology* (1863). His other papers and books number more than 200, on topics ranging from crustaceans to volcanoes, to texts reconciling science and religion, and covering geographic areas from California to the South Pacific.

See also mineral, mineralogy; North American geology.

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dark matter The mass in galaxies and galactic clusters inferred to exist by the rotational properties of galaxies, the bending of light, and other techniques but has not been confirmed to exist by observations at any electromagnetic wavelength is known as dark matter. Dark matter is mysterious; with an unknown composition it interacts only very weakly with normal matter and has been decoupled from the rest of the universe since before the time primordial nucleosynthesis began. Scientists believe that dark matter has experienced large fluxuations in its density distribution since early in the history of the universe, without affecting the background radiation of the universe, but effectively forming large-scale clumping and other mass distributions in the universe. In this way dark matter is able to control the overall mass distribution in the universe without affecting the microwave background radiation or any other observational constraints on the universe.

The large gravitational attraction of dark matter is theorized to have drawn gas and other matter into the vicinity of peaks in its distribution over the history of the universe, accounting for the distribution of galaxies and clusters observed today. One of the shocking features of dark matter is that, although it cannot be seen or directly observed, it is thought to make up the bulk of the universe. About 4 percent of the universe is thought to be made of visible matter, about 22 percent is estimated to be dark matter, and a remarkable 74 percent of the universe is thought to be dark energy. Dark energy permeates the entire universe and is thought to be the cause of the recently detected increase in the rate of expansion of the universe. Dark energy has been proposed to consist of two forms, including the cosmological constant, a constant form of energy that fills space homogeneously, and other more exotic forms of energy (known as scalar fields with names such as moduli and quintessence) that vary in time and in space.

Astrophysicists have classified dark matter into two basic theoretical types, hot and cold, based on its temperature at the time the galaxies began to form. Whether the dark matter was hot or cold at the time the galaxies formed results in vastly different structures for the universe in later times. Astrophysicists and cosmologists have used this variation to model the evolution and structure of the universe using different combinations of hot and cold dark matter as gravitational building blocks. This work is purely theoretical, carried out by simulations in supercomputers, since dark matter has never been directly observed.

Hot dark matter is thought to be made of very lightweight particles, even lighter than electrons. Some astrophysicists think that hot dark matter may be composed of neutrinos. Models for the evolution of the universe using hot dark matter account for the development of very large-scale structures, such as superclusters, and vast empty regions called voids, but they do not explain the smaller-scale structures very well. This is because small amounts of hot material tend to disperse, not to group together to help form smaller-scale structures. Therefore most astrophysicists suggest that models for the evolution of the universe that rely only on hot dark matter are not feasible.

Cold dark matter is thought to consist of heavy particles that formed in the earliest microseconds (10^{-43} second after the big bang) at a time when the strong, weak, and electromagnetic forces were still unified (a time known as the grand unified theory time). Unlike the (theoretical) hot dark matter, computer models for the origin of the universe that use cold dark matter can explain the formation of both large-scale and small-scale structures in the universe. Most astrophysicists and cosmologists therefore prefer models of dark matter that suggest it consists of heavy cold particles that formed very soon after the big bang.

Some new models for the universe suggest that dark matter may consist of both hot and cold particles. Supercomputer simulations can match the theoretical evolution of the universe and its current structure with what might have happened by specific mixtures of hot and cold dark matter.

See also ASTRONOMY; ASTROPHYSICS; COSMIC MICROWAVE BACKGROUND RADIATION; COSMOLOGY; ORIGIN AND EVOLUTION OF THE UNIVERSE.

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Darwin, Charles (1809–1882) British *Natural Historian, Geologist, Evolutionist* Charles Darwin was a British naturalist well known for his theory of evolution by means of natural selection. He proposed that all species of life have evolved over time from common simple ancestors. His ideas on the transmutation of species and natural selection were conceived in 1838 but not published until 1859. These ideas were used to build the modern concept of evolution and form some of the basic foundations of biology by offering viable explanations for the diversity of life, expressed in his famous book *On the Origin of Species,* published in 1859. His ideas are widely accepted by the scientific community but are often still attacked by religious fundamentalist communities. Darwin, who ranks as one of the most influential natural scientists of the 19th century, also made many observations and published several books on the geological sciences. His notes from a five-year-long voyage from 1831 to 1836 on the voyage of the HMS *Beagle* demonstrated his prowess as a geologist, following the uniformitarian principles of Scottish geologist Charles Lyell. Darwin also wrote about the origin of humans in his *The Descent of Man, and Selection in Relation to Sex,* published in 1871. Charles Darwin's contributions and influence in science were so great that when he died in 1882 he was honored with a state funeral in London and buried at Westminster Abbey.

EARLY YEARS

Charles Robert Darwin was born on February 12, 1809, in Shrewsbury, England, the fifth of six children born to the wealthy doctor and financier Robert Darwin and Susannah Wedgwood Darwin. Susannah died when Charles was only eight, and he then joined his older brother Erasmus as a border at the Anglican Shrewsbury School.

At the age of 16 Charles spent the summer of 1825 as an apprentice doctor helping his father treat the poor of Shropshire in the West Midlands region of England. He then returned to medical school in Edinburgh, but he was not interested in surgery, so instead he learned taxidermy from John Edmonston, a freed slave who had worked for English naturalist Charles Waterton (1782–1865) in the South American rain forest. In 1826 in the second year of his studies at Edinburgh, Darwin joined the Plinian Society, a student-run organization dedicated to the study of natural history under the guidance of Dr. Robert Grant. In 1827 Darwin made a presentation to this group about his studies that black "spores" found in oyster shells in the Firth of Forth were the eggs of a skate leech species. He spent much time during these years studying the collections of plants at the University Museum, while neglecting his course work in the geology course of Robert Jameson.

Darwin's father was worried about the direction of his son's studies, drifting further from the medical field, and he enrolled him in a bachelor of arts program at Christ's College in Cambridge, with hopes that he would become a clergyman with a steady income. Darwin instead sought company riding horseback and shooting in the countryside, while becoming engrossed in beetle collecting that eventually led him to publish his work in *Stevens' Illustrations of British Entomology*. These investigations led him to become friends with botany professor John Stevens Henslow, who helped Darwin investigate natural sciences, mathematics, religious studies, and physics, passing his exams as 10th in his class of 178 in 1831.

Darwin continued to study theology and science at Cambridge, where he read William Parley's books on natural theology and his arguments for divine design in nature. His courses and studies inspired Darwin to travel and contribute to science, and he planned to visit Tenerife in the tropical Canary Islands in the Atlantic Ocean to study the natural history of the region. He took the geology course of Adam Sedgwick, traveling to Wales for fieldwork, and when he returned to Cambridge he found that his friend John Stevens Henslow had recommended him to the unpaid position of naturalist on a voyage of the HMS *Beagle* under Captain Robert Fitzroy. Darwin's father initially objected to his participation on the journey but eventually relented, and Darwin left on the historic voyage four weeks later in 1831.

VOYAGE OF THE HMS *BEAGLE*

Darwin left England aboard HMS *Beagle* on December 27, 1831, under the command of Captain Robert Fitzroy. The *Beagle* voyaged across the Atlantic Ocean, while the crew carried out hydrographic surveys around the coasts of southern South America, then sailed to Tahiti and Australia, returning nearly five years later on October 2, 1836. Throughout this voyage, the second for the *Beagle,* Darwin spent most of his time, 39 months out of the 57-month-long voyage, exploring on land. This time was dedicated to his studies of geology, collecting fossils, and making detailed observations of plants and animals that would later form the basis for his theory of evolution by natural selection.

Several times during the voyage of the *Beagle* Darwin sent his notes and samples back to Cambridge, along with letters to his family. These materials focused on his areas of expertise in geology, beetle collecting, and marine invertebrates, but also increasingly on zoology and related biological subjects in which he was a novice. In the seacliffs of Patagonia he discovered extinct fossil species including skeletons of giant mammals, which he named *Megatherium* (now known to be a type of giant ground sloth that lived from 2 million to 8,000 years ago) and shipped back to England. Also in Patagonia Darwin noted that some areas showed stepped terraces along the coast, and each had seashells along the flat surfaces. He correctly interpreted the terraces to reflect that the land was rising relative to the sea, and these shelves represented former shorelines. While in Chile Darwin experienced a major earthquake and noticed that many mussel beds were stranded above the high-water mark, reminiscent of the raised beaches he saw in Tierra del Fuego. While high in the Andes Darwin found beds of marine shelly fossils and beach deposits; he inferred that these ranges had been uplifted from the sea.

The *Beagle* visited the Galápagos Islands in September and October 1835, then traveled to other islands including atolls in the Pacific. Darwin investigated the coral reefs around these islands and hypothesized that the volcanic islands gradually sank below sea level, and as they did the corals grew upward, eventually forming a ring of coral reefs surrounding a sunken island. While in the Galápagos, Darwin found that different types of mockingbirds were on different islands, and from this he inferred, nearly a quarter century later, that the different species evolved separately on each island, from a common ancestor. While the *Beagle* was at the Galápagos, Darwin also collected many samples of finches. At the time, however, he did not appreciate the differences between them, and only after he returned to England and shared the finches with the ornithologist John Gould on January 4, 1837, did he recognize that the finches represented 12 separate species. After more work Darwin appreciated that the finches, mockingbirds, and also tortoises had similar ancestors on the South American mainland and had all evolved into distinct species on each of the separate islands of the Galápagos. The term *Darwin's finches* was coined by English ornithologist Percy Lowe for these birds in 1936 and popularized by British ornithologist David Lack (1910–73) in 1947.

DARWIN'S THEORY OF EVOLUTION

When Darwin returned to London he was already a celebrity in some scientific circles, since his mentor Henslow had shared many of his geological notes and biological findings with colleagues. After visiting family and friends Darwin returned to Cambridge and studied his notes, data, and samples with the help of many colleagues and scientists recommended by Henslow. Together they cataloged his collections from around the world and discussed many of the possibilities suggested by his geological findings and, most famously, discussed ideas about the variety of different species in the plant and animal kingdoms and whether or not species were immutable, as commonly assumed in those times. Darwin met British geologist Charles Lyell (1797–1875), with whom he discussed uniformitarianism. Lyell introduced Darwin to the young anatomist Richard Owen, and together they identified several extinct species that closely resembled living species in South America.

In December 1836 Darwin began writing up much of his work. He surmised that the South American continent was slowly rising and presented this idea to the Geological Society of London on January 4, 1837, the same day he presented his collections of mammals and birds to the zoological society, where ornithologist John Gould identified the Galápagos birds as 12 separate species of finches. Darwin moved to London and continued his work and discussions with other scientists. By spring and summer 1837 Darwin's notebooks showed that he had derived his ideas that different species transmuted into other species and formed a branching evolutionary tree in which species merged backward in time to common ancestors. Darwin worked long hours and formally recorded his ideas in his journal in summer 1837. He had classified his numerous biological collections and derived the following ideas:

- Evolution did occur.
- Evolutionary change to form new species was gradual, requiring up to 3 million years.
- Natural selection was the main driving force for evolution.
- All the species of life that are present today came from a single unique life-form.

Darwin's theory states that within each species nature randomly selects which animal or plant will survive and which will die out. Survival depends on how adaptable the species is to its surrounding dynamic environment.

By September 1837 Darwin developed health problems, including heart palpitations, and he rested for a while in the country. While there he observed the work of earthworms, then delivered a talk on the subject to the Geological Society in November, and in March 1838 Darwin became secretary of the society. His long hours of work took their toll, and Darwin developed more health problems such as stomach ailments, headaches, and heart symptoms, which caused him to be laid up for days at a time.

On November 11, 1838, Darwin proposed marriage to his cousin Emma Wedgwood, and she accepted. They were married on January 29, 1839, five days after the Royal Society of London elected him a fellow.

The Darwins returned to London, and for the next decade he prepared the results of his research for scientific publication. These works included his Journal and Remarks (*The Voyage of the Beagle*) published in 1839, and a book on coral reefs published in 1842. After this Darwin and his family moved to Down House outside London, so he could work in a more peaceful setting. Darwin's health continued to fluctuate, and in 1851 his daughter Annie became gravely ill and died. This loss led Darwin to abandon his faith in religion.

Darwin continued working to publish his main ideas, sometimes fearing he would die before his work was complete. In June 1858 a correspondence with the British naturalist Alfred Russel Wallace about the introduction of species and natural selection shocked Darwin, as it included a paper Wallace had written describing natural selection. Wallace and Darwin decided to present their work together at a meeting of the Linnean Society on July 1, 1858, but, tragically, just before the meeting, Darwin's baby son died of scarlet fever so he was unable to attend. Darwin's health continued to decline, and his works were not completed.

After another 13 months in preparation, Darwin arranged for his book on natural selection to be published in 1859 through British publisher John Murray (1745–93). The book, *On the Origin of Species by Means of Natural Selection or the Preservation of Favored Races in the Struggle of Life,* proved to be immensely popular as soon as it was published, with all 1,250 copies sold before publication. The text caused great controversy, especially with various religious institutions. Even some of Darwin's former tutors at Cambridge, including Sedgwick and Henslow, opposed the ideas in his book. It was said that his theories went against the teachings of the church, although perhaps some of his colleagues had merely been afraid to speak out against the church. Some liberal clergymen, however, spoke in favor of Darwin's ideas, calling them noble conceptions of deity. Darwin did not discuss religious views in his works, though he was in fact a very religious man (before his daughter's death), but other scientists after him have used his work as a basis of their own theories that there is no room for religion in science.

Darwin continued to work in the fields of botany, geology, and zoology, publishing works including *Variation in Plants and Animals under Domestication* (1868), followed by *The Descent of Man, and Selection in Relation to Sex* (1871). In 1872 Darwin published *Expression of the Emotions in Man and Animals,* followed by several books on plants, including insectivorous plants, and an insightful volume on *The Power of Movement in Plants,* describing heliotropism and phototropism in plants, published in 1880, and a final book on earthworms.

Darwin died on April 19, 1882, and was buried in a state funeral at Westminster Abbey, near Sir Issac Newton and John Herschel. Charles and Emma Darwin had 10 children, three of whom (Annie, Mary, and Charles Waring) died in childhood, and seven of whom survived Charles. These included Charles Erasmus, Henrietta Emma, George Howard, Elizabeth Bessy, Francis, Leonard, and Horace.

See also EVOLUTION; HISTORICAL GEOLOGY; LYELL, SIR CHARLES.

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deformation of rocks Deformation of rocks is measured by three components: strain, rotation, and translation. Strain measures the change in shape and size of a rock, rotation measures the change in orientation of a reference frame in the rock, and translation measures how far the reference frame has moved between the initial and final states of deformation.

The movement of the lithospheric plates causes rocks to deform, creating mountain belts and great fault systems like the San Andreas. The terms *strain* and *stress* describe how rocks are deformed. Stress, a measure of force per unit area, is a property that has directions of maximum, minimum, and intermediate values. *Strain* describes the changes in the shape and size of an object, and it is a result of stress.

There are three basic ways by which a solid can deform. The first is by elastic deformation, which is a reversible deformation exemplified by a stretching rubber band or the rocks next to a fault that bend and then suddenly snap back to place during an earthquake. Most rocks can undergo only a small amount of elastic deformation before they suffer permanent irreversible, nonelastic strain. Elastic deformation obeys Hooke's law, which simply states that for elastic deformation, a plot of stress versus strain yields a straight line. In other words strain is linearly proportional to the applied stress. So for elastic deformation, the stressed solid returns to its original size and shape after removal of the stress.

Solids may deform through fracturing and grinding processes during brittle failure or by flowing

San Andreas Fault crossing Carrizo Plain in California *(Bernhard Edmaier/Photo Researchers, Inc.)*

during ductile deformation processes. Fractures form when solids are strained beyond the elastic limit and the rock breaks; they are permanent, or irreversible, strains. Ductile deformation is also irreversible, but the rock changes shape by flowing, much like toothpaste squeezed out of a tube.

When compressed, rocks first experience elastic deformation, then as the stress increases they hit the yield point, at which ductile flow begins, and eventually the rock may rupture. Many variables determine why some rocks deform by brittle failure and others by ductile deformation. These variables include temperature, pressure, time, strain rate, and composition. The higher the temperature of the rock during deformation, the weaker and less brittle the rock will be. High temperature therefore favors ductile deformation mechanisms. High pressures increase the strength of the rock, leading to a loss of brittleness, and therefore hinder fracture formation. Time is also an important factor determining which type of deformation mechanism may operate. Fast deformation favors the formation of brittle structures, whereas slow deformation favors ductile deformation mechanisms. Strain rate is a measure of how much deformation (strain) occurs over a given time. Slow deformation rates favor ductile deformation, whereas fast deformation rates favor brittle deformation. Finally, the composition of the rock is also important in determining what type of deformation will occur. Some minerals (like quartz) are relatively strong, whereas others (such as calcite) are weak. Strong minerals or rocks may deform by brittle mechanisms under the same (pressure, temperature) conditions that weak minerals or rocks deform by ductile flow. Water reduces the strength of virtually all minerals and rocks; therefore the presence of even a small amount of water can significantly affect the type of deformation that occurs.

BENDING OF ROCKS

The bending or warping of rocks is called folding. Monoclines are folds in which both sides are horizontal, which often form over deeper faults. Anticlines are upward-pointing arches that have the oldest rocks in the center, and synclines are downward-pointing arches, with the oldest rocks on the outside edges of the structure. Though many other geometric varieties of folds exist, most are variations of these basic types. The fold hinge is the region of maximum curvature on the fold, whereas the limbs are the regions between the fold hinges. Folds may be further classified according to how tight the hinges are, which can be measured by the angle between individual fold limbs. Gentle folds have interlimb angles between 180° and 120°, open folds have interlimb angles between 120° and 70°, close folds between 70° and 30°, tight folds have interlimb angles of fewer than 30°, and isoclinal folds have interlimb angles of 0°. Folds may be symmetrical, with similar lengths of both fold limbs, or asymmetrical, in which one limb is shorter than the other limb. Fold geometry may also be described by using the orientation of an imaginary surface (the axial surface), that divides the fold limbs into two symmetric parts, and the orientation of the fold hinge. Folds with vertical axial surfaces

Folded rock strata in Austrian Alps *(Bernhard Edmaier/Photo Researchers, Inc.)*

and subhorizontal hinges are known as upright gently plunging folds, whereas folds with horizontal hinges and axial surfaces are said to be recumbent.

BREAKING OF ROCKS

Brittle deformation results in the breaking of rock along fractures. Joints are fractures along which no movement has occurred. These may be tectonic structures formed in response to regional stresses or formed by other processes such as cooling of igneous rocks. Columnar joints are common in igneous rocks, forming six-sided columns when the magma cools and shrinks.

Fractures along which relative displacement has occurred are known as faults. Most faults are inclined surfaces. The block of rock above the fault is the hanging wall, and the block beneath the fault is the footwall, after old mining terms. Faults are classified according to their dip and the direction of relative movement across the fault. Normal faults are faults along which the hanging wall has moved down relative to the footwall. Reverse faults are faults along which the hanging wall moves up relative to the footwall. Thrust faults are a special class of reverse faults that dip fewer than 45°. Strike-slip faults are steeply dipping (nearly vertical) faults along which the principal movement is horizontal. The sense of movement on strike-slip faults may be right lateral or left lateral, determined by standing on one block and describing whether the block across has moved to the right or to the left.

REGIONAL DEFORMATION OF ROCKS

Deformation of rocks occurs at a variety of scales, from the atomic to the scale of continents and entire tectonic plates. Deformation at the continental-to-plate scale produces distinctive regional structures. Cratons, large stable blocks of ancient rocks that have been stable for a long time (since 2.5 billion years ago), form the cores of many continents and represent continental crust that was formed in the Archean Era. Most cratons are characterized by thick continental roots made of cold mantle rocks, by a lack of earthquakes, and by low heat flow.

Orogens, or orogenic belts, are elongate regions that represent eroded mountain ranges, and they typically form belts around older cratons. Characterized by abundant folds and faults, they typically show shortening and repetition of the rock units by 20–80 percent. Young orogens are mountainous—for instance, the Rocky Mountains have many high peaks, and the slightly older Appalachians have lower peaks.

Continental shields are places where ancient cratons and mountain belts are exposed at the surface, whereas continental platforms are places where younger, generally flat-lying sedimentary rocks overlie the older shield. Many orogens contain large portions of crust that have been added to the edges of the continental shield through mountain-building processes related to plate tectonics. Mountain belts may be subdivided into three basic types: fold and thrust belts, volcanic mountain chains, and fault block ranges.

FOLD AND THRUST BELTS

Fold and thrust mountain chains are contractional features, formed when two tectonic plates collide, forming great thrust faults and folding metamorphic rocks and volcanic rocks. By examining and mapping the structure in the belts we can reconstruct their history and essentially pull them back apart in the reverse of the sequence in which they formed. By reconstructing the history of mountain belts in this way, we find that many of the rocks in the belts were deposited on the bottom of the ocean or on the ocean margin deltas and continental shelves, slopes, and rises. When the two plates collide, many of the sediments get scraped off and deformed, creating the mountain belts; thus fold and thrust mountain belts mark places where oceans have closed.

The Appalachians of eastern North America represent a fold and thrust mountain range. They show a detachment surface, or decollement, folds, and thrust faults. The sedimentary rocks in the mountain belt are like those now off the coast, so the Appalachians are interpreted to represent a place where an old ocean has closed.

VOLCANIC MOUNTAIN RANGES

Volcanic mountain ranges represent thick segments of crust that formed by addition of thick piles of volcanic rocks, generally above a subduction zone. Examples of volcanic mountain chains include the Aleutians of Alaska, the Fossa Magna of Japan (including Mount Fuji), and the Cascades of the western United States (including Mount Saint Helens). These mountain belts are not formed primarily by deformation but by volcanism associated with subduction and plate tectonics. Many do have folds and faults, however, showing that there is overlap between fold and thrust types of mountain chains and volcanic ranges.

FAULT-BLOCK MOUNTAINS

Fault-block mountains generally form by extension of the continental crust. The best examples include the Basin and Range Province of the western United States, and parts of the East African Rift System, including the Ethiopian Afar. These mountain belts are formed by the extension or pulling apart of the continental crust, forming basins between individual tilted fault-block mountains. These types of ranges are associated with thinning of the continental crust, and some have active volcanism as well as active extensional deformation.

See also OROGENY; PLATE TECTONICS; STRUCTURAL GEOLOGY.

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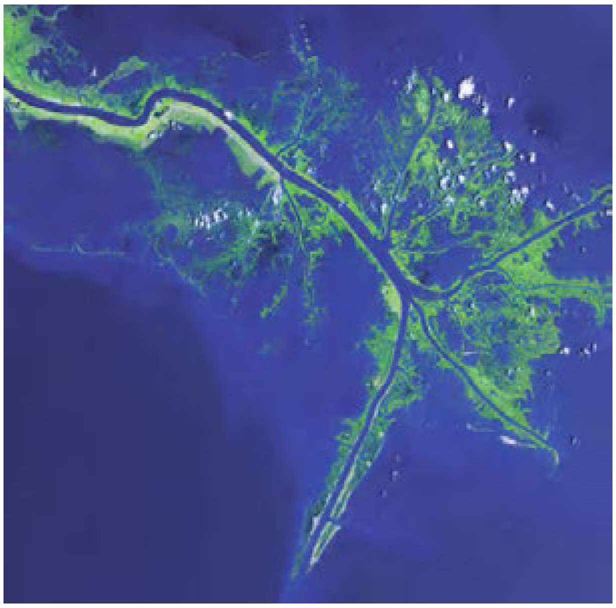
deltas Found at the mouths of streams and rivers, deltas are low, flat deposits of alluvium that form broad triangular or irregular-shaped areas that extend into bays, oceans, or lakes. They are typically crossed by many distributaries from the main river and may extend for a considerable distance underwater. Deltas are extremely sensitive coastal environments and are particularly susceptible to the effects of rising sea level and human activities. Since deltas are the sites of rich oil deposits, there is currently a sensitive interplay between meeting the world's energy needs by extracting oil from beneath the fragile delta environment and the environmental concerns about preserving the delta ecosystem.

The velocity of the water and capacity of a river or stream to hold sediment in suspension suddenly drop when it enters the relatively still body of water such as a lake or the ocean. Thus the stream dumps its sediment load here, and the resulting deposit is known as a delta. The term *delta* was first used for these deposits by Herodotus in the fifth century B.C.E. for the triangular-shaped alluvial deposits at the mouth of the Nile River. The stream first drops the coarsest material, then progressively finer material farther out, forming a distinctive sedimentary deposit. In a study of several small deltas in ancient Lake Bonneville in Utah, Idaho, and Nevada, American geologist Grover Karl Gilbert in 1890 recognized that the deposition of finer-grained material farther away from the shoreline also created a distinctive vertical sequence in delta deposits. The resulting foreset layer is thus graded from coarse nearshore to fine offshore. The bottomset layer consists of the finest material, deposited far out. As this material continues to build outward, the stream must extend its length and forms new deposits, known as topset layers, on top of all this. Topset beds may include a variety of subenvironments, both subaqueous and subaerial, formed as the delta progrades seaward.

Most of the world's large rivers, such as the Mississippi, the Nile, and the Ganges, have built enormous deltas, yet all of these are different in detail. Deltas may have various shapes and sizes or may even be completely removed, depending on the relative amounts of sediment deposited by the stream, the erosive power of waves and tides, the climate, and the tectonic stability of the coastal region. Most deltas are located along passive or trailing continental margins, and few are found along convergent boundaries (exceptions include the Copper River in Alaska and the Fraser River in British Columbia). This is largely because river systems on passive margins tend to be long and to drain huge areas composed of easily eroded soil, carrying large sediment loads. Rivers along active margins tend to be much shorter and cut through bedrock, which is not eroded as easily so yields smaller sediment loads. Additionally, convergent margins do not contain wide continental shelves needed for the delta to be deposited on, but instead are marked by deep-sea trenches where sediments are rapidly deformed and buried.

Most deltas are quite young, having formed since the glaciers melted 18,000–10,000 years ago and sea levels rose onto the continental shelves. During the last glacial maximum when glaciers were abundant for much of the period from 2.5 million years ago until about 18,000 years ago, sea levels were about 395 feet (120 m) lower than at present. During the glacial maximum, most rivers eroded canyons across the continental shelves and carried their sedimentary



False-color composite of Mississippi River delta from ASTER instrument on NASA's *Terra* satellite, May 24, 2001 *(USGS EROS Data Center Satellite Systems Branch as part of "Earth as Art II" image series, NASA)*

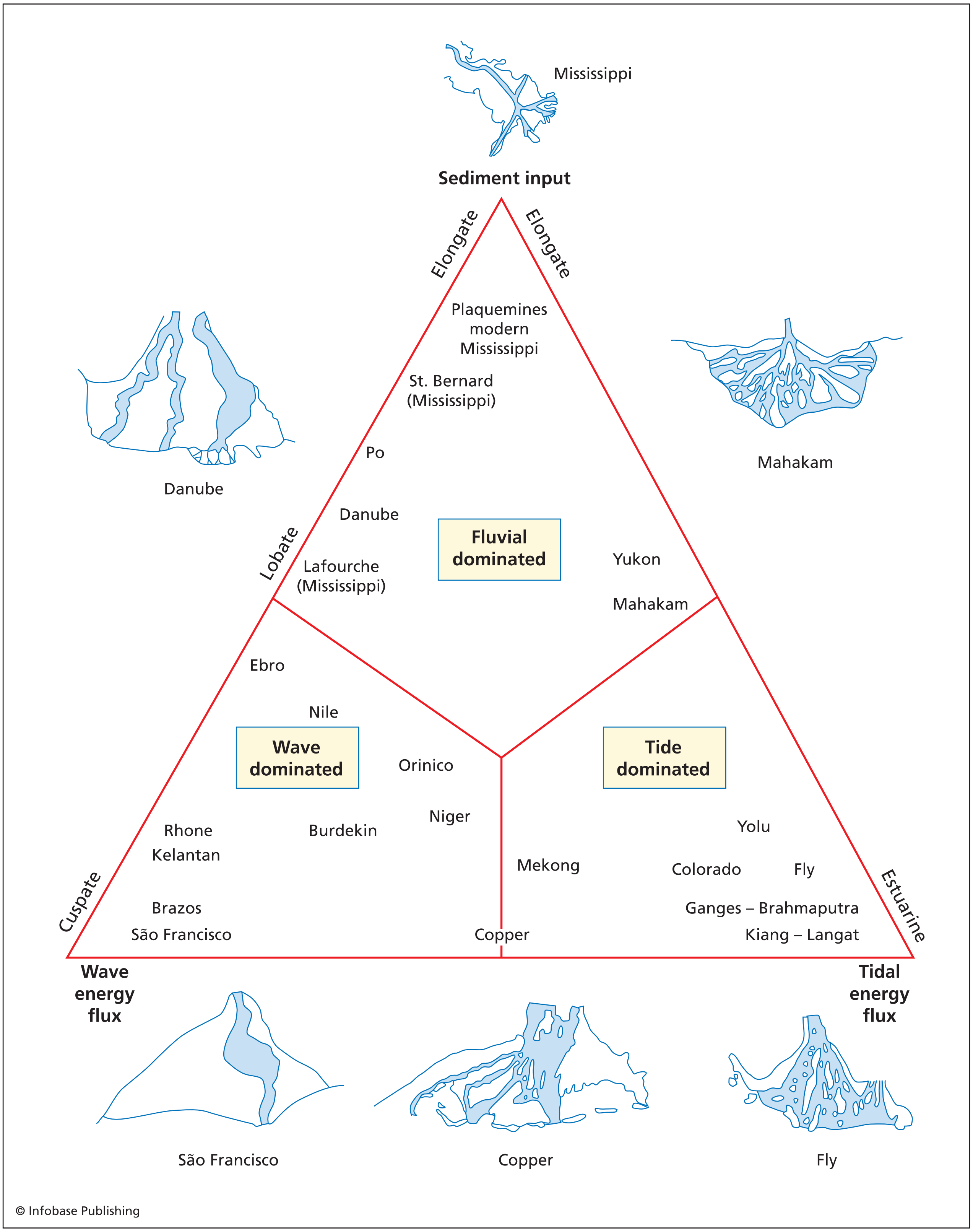
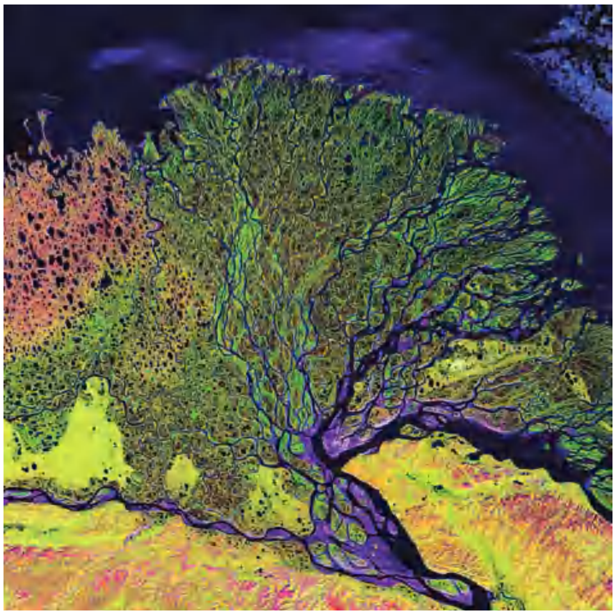


Diagram illustrating different types of deltas formed as a result of different relative influence of sediment supply, tidal energy flux, and wave energy flux. The shapes of deltas characteristic of each are shown on the edges of the diagram, and names of other deltas are plotted in the space inside the diagram, in positions that reflect the relative strength of each component for each delta.

load to the deep oceans. As the glaciers melted, sea level rose onto the broad continental shelves of many continents, where wide and thick delta sediments have space to accumulate. Nearly all of the active parts of deltas are younger than 18,000 years, but many have older, deeper parts that formed during older sea-level high stands (some from interglacial periods) that have subsided deep below sea level. As sea levels were initially rising fast as the glaciers were undergoing rapid melting, the river mouths were moving so rapidly inland that deltas did not have time to form. The rate of sea-level rise slowed significantly around 6,000 years ago, and most of the world's deltas began to grow significantly since that time. This history of sedimentation is reflected in the Mississippi River delta, which has components that are older than several million years, but the active lobes only began forming about 6,000 years ago.

Deltas exhibit a range in conditions and environments from terrestrial and river–dominated at their landward boundaries to marine and wave and tide–dominated at their fronts. The mere presence of a delta along a coast indicates that the amount of sediment input by the river is greater than the amount of sediment that can be removed by the action of waves, tides, currents, wind, and submarine slumping. The distributaries and main channel of the rivers forming deltas typically move to find the shortest route to the sea, and this causes shifting of the active locus of deposition on deltas. Inactive areas, which may form lobes or just parts of the delta, typically subside and are reworked by tidal currents and waves. The processes involved in the growth or seaward progradation of deltas result in the formation of many environments, including those influenced by subaerial, intertidal, and subaqueous processes, and include freshwater, brackish, and saltwater conditions. Most deltas can be divided into three main parts: the landward delta plain, the delta front, and the prodelta in the subtidal to deep continental shelf environment.

The delta plain is really a coastal extension of the river system. It comprises river and overbank sedimentary deposits in a flat, meandering stream-type of setting. These environments are at or near (or in some cases below) sea level, and it is essential that the overbank regions receive repeated deposits of muds and silts during flood stages to build up the land surface continuously as the entire delta subsides below sea level by tectonic processes. Deltas deprived of this annual silt by the construction of levees gradually sink below sea level. If homes were built on delta flood plains without levees, however, they would gradually be buried in mud, as opposed to sinking below sea level behind the false protection of a levee. The stream channels are bordered by natural levee systems that may rise several feet (1–2 m) above the floodplain; these areas are often the only places above water level during river flood stages. In many outer delta plains the only places above sea level are the natural levees. During floods the levees sometimes break, creating a crevasse splay that allows water and muddy sediment to flow rapidly out of the channel and cover the overbank areas, plus any homes or other human infrastructure built in this sensitive area.



False-color image of Lena delta in Russia acquired by Landsat 7's Enhanced Thematic Mapper plus sensor on February 27, 2000 *(USGS EROS Data Center Satellite Systems Branch)*

The delta front environment, located on the seaward edge of the delta, is an extremely sensitive environment. It is strongly affected by waves, tides, changing sea level, and changes in the flux or amount of sediment delivered to the delta front. Many delta fronts have an offshore sandbar, called a distributary mouth bar, or barrier island system, parallel to the coast along the delta front. Some deltas, such as the Mississippi, are losing huge areas of delta front to subsidence below sea level, due to combined effects of a decrease in sediment supply to the delta front, tectonic subsidence, sea-level rise, human activities such as oil drilling and building levees, and severe erosion from storms such as Hurricanes Hugo, Katrina, and Ike.

Deltas have been classified various ways over time, including by schemes based on their shapes and on the processes involved in their construction. High-constructive deltas form where the fluvial transport dominates the energy balance on the delta. These deltas dominated by riverine processes are typically elongate, such as the modern delta at the mouth of the Mississippi, which has the shape of a bird's foot, or they may be lobate, such as the older Holocene lobes of the Mississippi that have now largely subsided below sea level.

High-destructive deltas form where the tidal and wave energy is high and much of the fluvial sediment gets reworked before it is finally deposited. In wave-dominated, high-destructive deltas sediment typically accumulates as arcuate barriers near the mouth of the river. Examples of wave-dominated deltas include the Nile and the Rhône. In tide-dominated, high-destructive deltas, tides rework the sediment into linear bars that radiate from the mouth of the river, with sands on the outer part of the delta sheltering a lower-energy area of mud and silt deposition inland from the segmented bars. Examples of tide-dominated deltas include the Ganges, and the Kikari and Fly River deltas in the Gulf of Papua New Guinea. Other rivers drain into the sea in places where the tidal and wave current is so strong that these systems completely overwhelm the fluvial deposition, removing most of the delta. The Orinoco River in South America has had its sediment deposits transported southward along the South American coast, with no real delta formed at the mouth of the river.

Where a coarse sediment load of an alluvial fan dumps its load in a delta, the deposit is known as a fan-delta. Braid-deltas are formed when braided streams meet local base level and deposit their coarse-grained load.

Deltas create unique, diverse environments where fresh and saltwater ecosystems meet, and swamps, beaches, and shallow marine settings are highly varied. They contain some of the most productive ecological areas in the world. Deltas also form some of the world's greatest hydrocarbon fields, however, as the muds and carbonates make good source rocks and the sands make excellent trap rocks. Thus there is a delicate struggle between preserving natural ecosystems and using the planet's resources that must be maintained on the deltas of the world. Resting at sea level, delta environments are also the most susceptible to disaster from hurricanes and coastal storms.

See also BASIN, SEDIMENTARY BASIN; BEACHES AND SHORELINES; SEDIMENTARY ROCK, SEDIMENTATION; SUBSIDENCE.

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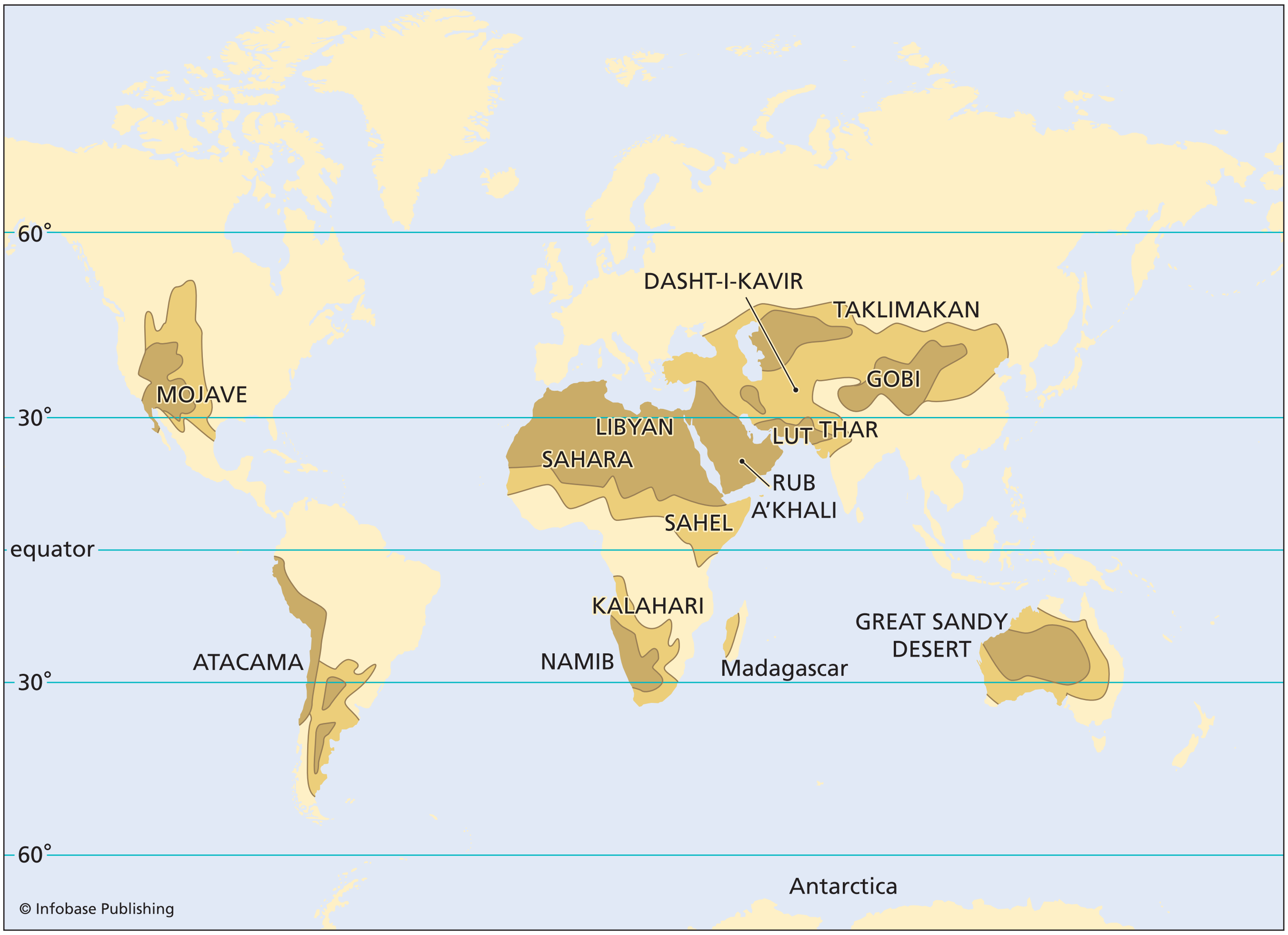
deserts The driest places on Earth, deserts by definition receive less than one inch (250 mm) of rain per year. Most deserts are so dry that more moisture is able to evaporate than falls as precipitation. At present about 30 percent of the global landmass is desert, and the United States has about 10 percent desert areas. With changing global climate patterns and shifting climate zones, much more of the planet is in danger of becoming desert.

Most deserts are also hot, with the highest recorded temperature on record being 136°F (58°C) in the Libyan Desert. With high temperatures the evaporation rate is high, and in most cases deserts evaporate more than the amount of precipitation that falls as rain. Many deserts evaporate 20 times the amount of rain that falls, and some places, like much of the northern Sahara, are capable of evaporating 200–300 times the amount of rain that falls in rare storms. Deserts are also famous for large variations in daily temperature, sometimes changing as much as 50–70°F (28–39°C) between day and night (called a diurnal cycle). These large temperature variations can be enough to shatter boulders. Deserts are also windy and are prone to sand and dust storms. The winds arise primarily because the heat of the day causes warm air to rise and expand, and other air must rush in to take its place. Airflow directions also shift frequently between day and night (in response to the large temperature difference between day and night), and between any nearby water bodies, which tend to remain at a constant temperature over a 24-hour period.

There are many different types of deserts located in all different parts of the world. Some deserts are associated with patterns of global air circulation, and others form because they are in continental interiors far from any sources of moisture. Deserts can form on the "back," or leeward, side of mountain ranges,



World map showing location of deserts: Note how most deserts are concentrated between 15° and 30° latitude.

where downwelling air is typically dry, or they can form along coasts where cold, upwelling ocean currents lower the air temperature and lower its ability to hold moisture. Deserts can also form in polar regions, where extremely dry and cold air can evaporate (or sublimate) much more moisture than falls as snow in any given year. Parts of Antarctica have not had any significant ice or snow cover for thousands of years.

Deserts have a distinctive set of landforms and hazards associated with these landforms. The most famous desert landform is a sand dune, a mobile accumulation of sand that shifts in response to wind. Deserts tend to be very windy, and some of the hazards in deserts are associated with sand and dust carried by the wind. Dust eroded from deserts can be carried around the world and is a significant factor in global climate and sedimentation. Some sandstorms are so fierce that they can remove paint from cars or skin from an unprotected person. Other desert hazards are associated with flash floods, debris flows, avalanches, extreme heat, and extreme temperature fluctuations.

Droughts are different from deserts—a drought is an extended lack of rainfall across a region that typically gets more rainfall. If a desert normally receives a small amount of rainfall and it still is getting little rainfall, then it is not experiencing a drought. In contrast, a different area that receives more rainfall than the desert may be experiencing a drought if it normally receives significantly more rainfall than it is at present. A drought-plagued area may become a desert if the drought is prolonged. Droughts can cause widespread famine, loss of vegetation, loss of life, and eventual death or mass migrations of entire populations.

Desertification is the conversion of previously productive lands to desert through a prolonged drought. Desertification may occur if the land is stressed before or during the drought, typically from poor agricultural practices, overuse of ground and surface water resources, and overpopulation. Global climate goes through several different variations that can cause belts of aridity to shift back and forth with time. The Sahel region of northern

DRYING OF THE AMERICAN SOUTHWEST

A drought is a prolonged lack of rainfall in a region that typically experiences a significant amount of precipitation. If a desert normally receives a small amount of rainfall, and it still is getting little rainfall, then it is not experiencing a drought. In contrast, a different area that normally receives more rainfall than the desert may be experiencing a drought if it normally receives significantly more rainfall than it is at present, even if it still experiences more rainfall than the desert. A drought-plagued area may become a desert if the drought is prolonged. Droughts are the most serious natural hazard in terms of their severity, area affected, loss of livelihood, social impact, and other long-term effects. Droughts can cause widespread famine, loss of vegetation, loss of life, and eventual death or mass migrations of entire populations.

Droughts may lead to the conversion of previously productive lands to desert. This process, called desertification, may occur if the land is stressed before or during the drought, typically from poor agricultural practices, overuse of ground and surface water resources, and overpopulation. Global climate undergoes several different variations that can cause belts of aridity to shift back and forth with time. The Sahel region of Africa has experienced some of the more severe droughts in recent times. The Middle East and parts of the desert southwest of the United States are overpopulated and the environment there is stressed. If major droughts occur in these regions, major famines could result and the land may be permanently converted to desert.

Much of the desert southwest region of the United States was settled in the past century following a century of historically high rainfall. Towns and cities grew, and the Bureau of Land Management diverted water from melting snows, rivers, and underground aquifers to meet the needs of growing cities. Some of the country's largest and newest cities, including Phoenix, Tucson, Denver, Las Vegas, Los Angeles, San Diego, and Albuquerque, have grown out of the desert using water from the Colorado River system. Even though the temperatures can be high, the air is good, and many people have chosen to move to these regions to escape crowded, polluted, or allergen-rich cities and air elsewhere. The surge in population has been met with increases in the water diverted to these cities, and fountains, swimming pools, resorts, golf courses, and green lawns have sprung up all over. In general the life can be comfortable.

In the past decade the water supply seems to be diminishing. Lake Powell in Arizona has shrunk to half its capacity, and the Colorado River flow shrunk to a quarter of its typical rates. The Colorado River typically supplies 30 million people with water and irrigates 4 million acres of fertile farmland, producing billions of dollars worth of crops. The massive water work systems across seven states in the Southwest were all built using river-flow data for the Colorado River based on 20th-century flow records. Now studies of the ancient climate history in the region going back thousands of years indicate that the 20th century may have been one of the wettest on record for the region. The Hoover Dam, the California aqueduct, and cities across the region were all built during this high-flow stage of the Colorado River, and water budgets for the region were calculated assuming these flows would continue. Now precipitation is decreasing, and the historical records show that the region regularly experiences droughts where the flow decreases to 80 percent and even 50 percent of the 20th-century values used for building the civilization in the desert southwest. Now that more than 80 percent of the water from the river is used for human consumption, droughts of this magnitude have severe implications for any community, and the water wars of the southwest may eventually start again. Historical records show that past civilizations such as the Anasazi in the region disappeared at the end of the 13th century during a similar drought period, and similar trends are expected by climate modelers for the future in the region.

Climate-change models released by the National Ocean and Atmospheric Administration show that the flow of the Colorado River may decrease to half of its 20th-century values by the middle of this century, and that these lower flow values will persist into the foreseeable future. The region is already experiencing rapid changes, with wildfires burning huge tracts of vegetation and occasional storms initiating mudflows and other desert processes. Climate models predict a likely descent of the region into dust bowl conditions, and these changes have already begun. The region saw many mega-droughts in medieval times and throughout history, and states of the region need to prepare for the likelihood of many years of water shortage and increasing drought conditions.

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Africa has experienced some of the more severe droughts in recent times. The Middle East and parts of the desert southwest of the United States are overpopulated and the environment is stressed. If major droughts occur in these regions, major famines could result and the land may be permanently desertified.

LOCATION AND FORMATION OF DESERTS

More than 30 percent of the planet's land area is arid or semiarid, and these deserts form an interesting pattern that reveals clues about how they develop. There are six main categories of desert, based on geographic location with respect to continental margins, oceans, and mountains: trade wind, or Hadley cell, deserts; continental interior/midlatitude deserts; rainshadow deserts; coastal deserts; monsoon deserts; and polar deserts.

TRADE WIND, OR HADLEY CELL, DESERTS

Many of the world's largest and most famous deserts are located in two belts between 15° and 30° North and South latitude. Included in this group of deserts are the Sahara, the world's largest desert, and the Libyan Desert of North Africa. Other members of this group include the Syrian Desert, Rub' al-Khali (Empty Quarter), and Great Sandy Desert of Arabia; the Dasht-e-Kavir, Lut, and Sind of southwest Asia; the Thar Desert of Pakistan; and the Mojave and Sonoran Deserts of the United States. In the Southern Hemisphere deserts that fall into this group include the Kalahari Desert of Africa and the Great Sandy Desert of Australia. The formation of the Atacama Desert in South America, the world's driest place, can be partly attributed to its location between these latitudes.

The location of these deserts is controlled by a large-scale atmospheric circulation pattern driven by energy from the Sun. The Sun heats equatorial regions more than high-latitude areas, which causes large-scale atmospheric upwelling near the equator. As this air rises, it becomes less dense and can hold less moisture, a condition leading to the formation of large thunderstorms in equatorial areas. This drier air then moves away from the equator at high altitudes, cooling and drying more as it moves, until it eventually forms two circumglobal downwelling belts between 15–30°N and S latitude. This cold downwelling air is dry and can hold much more water than it has brought with it on its circuit from the equator. These belts of circulating air, known as Hadley cells, are responsible for the formation of many of the world's largest, driest deserts. As this air completes its circuit back to the equator, it forms dry winds that heat up as they move toward the equator. The dry winds dissipate existing cloud cover and allow more sunlight to reach the surface, which consequently warms even more.

Deserts formed by global circulation patterns are particularly sensitive to changes in global climate; seemingly small changes in the global circulation can lead to catastrophic expansion or contraction of some of the world's largest deserts. For instance, the sub-Saharan Sahel has experienced several episodes of expansion and contraction, displacing or killing millions of people in this vicious cycle. When deserts expand, croplands dry up and livestock and humans cannot find enough water to survive. Desert expansion is the underlying cause of some of the world's most severe famines.

CONTINENTAL INTERIOR/ MIDLATITUDE DESERTS

Some places on Earth are so far from ocean moisture sources that by the time weather systems reach them, most of the moisture they carry has already fallen. This effect is worsened if the weather systems must rise over mountains or plateaus to reach these areas, because cloud systems typically lose moisture as they rise over mountains. These remote areas therefore have little chance of receiving significant rainfall. The most significant deserts in this category are the Taklimakan-Gobi region of China, resting south of the Mongolian steppe on the Alashan plateau, and the Karakum of western Asia. The Gobi is the world's northernmost desert, and it is characterized by 1,000-foot (305-m) high sand dunes made of coarser than normal sand and gravel, built up layer by layer by material moved and deposited by the wind. It is a desolate region, conquered successively by Genghis Khan, warriors of the Ming dynasty, then the People's Army of China. The sands are still littered with remains of many of these battles, such as the abandoned city of Khara Khoto. In 1372 Ming dynasty warriors conquered this walled city by cutting off its water supply, consisting of the Black River, waiting, then massacring anyone remaining in the city.

RAIN-SHADOW DESERTS

A third type of desert is found on the leeward, or back, side of some large mountain ranges, such as the sub-Andean Patagonian Gran Chaco and Pampas of Argentina, Paraguay, and Bolivia. A similar effect is partly responsible for the formation of the Mojave and Sonoran Deserts of the United States. These deserts form because as moist air masses move toward the mountain ranges, they must rise to move over the ranges. As the air rises it cools, and cold air cannot hold as much moisture as warm air. The clouds thus drop much of their moisture on the windward side of the mountains, explaining why places like the western Cascades and western Sierras of the United States are extremely wet, as are the western Andes in Peru. But the eastern lee, or back, sides of these mountains are extremely dry. This is because as the air rose over the fronts, or windward, sides of the mountains, it dropped its moisture. As the same air descends on the lee side of the mountains, it warms and can hold more moisture than it has left in the clouds. The result is that the air is dry and it rarely rains. This explains why places like the eastern sub-Andean region of South America and the Sonoran and Mojave Deserts of the western United States are extremely dry.

Rain-shadow deserts tend to be mountainous because of the way they form, and they are associated with a number of mass wasting hazards such as landslides, debris flows, and avalanches. Occasional rainstorms that make it over the blocking mountain ranges can drop moisture in the highlands, leading to flash floods coming out of mountain canyons into the plains or intermountain basins on the lee side of the mountains.

COASTAL DESERTS

Some deserts are located along coastlines, where intuition would seem to indicate that moisture should be plentiful. The driest place on Earth is the Atacama Desert, however, located along the coast of Peru and Chile. The Namib Desert of southern Africa is another coastal desert, known legendarily as the Skeleton Coast, because it is so dry that many of the large animals that roam out of the more humid interior climate zones perish there, leaving their bones sticking out of the blowing sands.

How do these coastal deserts form adjacent to such large bodies of water? The answer lies in the ocean currents, for in these places cold water upwells from the deep ocean and cools the atmosphere. The effect is similar to that of rain-shadow deserts, where cold air can hold less moisture, and the result is no rain.

MONSOON DESERTS

In some places seasonal variations in wind systems bring alternating dry and wet seasons. The Indian Ocean is famous for its monsoonal rains in the summer, as the southeast trade winds bring moist air onshore. As the clouds move across India, however, they lose moisture and must rise to cross the Aravalli Mountain range. The Thar Desert of Pakistan and the Rajasthan Desert of India are located on the lee side of these mountains and do not generally receive this seasonal moisture.

POLAR DESERTS

A final class of deserts is the polar desert, found principally in the Dry Valleys and other parts of Antarctica, parts of Greenland, and northern Canada. Approximately 3 million square miles (7.8 million km^2) on Earth consists of polar desert environments. In these places cold downwelling air lacks moisture, and the air is so dry that the evaporation potential is much greater than the precipitation. Temperatures do not exceed 50°F (10°C) in the warmest months, and precipitation is less than one inch (2.5 cm) per year. There are places in the Dry Valleys of Antarctica that have not been covered in ice for thousands of years.

Polar deserts are generally not covered in sand dunes but are marked by gravel plains or barren bedrock. The landforms of polar deserts are shaped by frost wedging, where alternating freeze-thaw cycles allow small amounts of water to seep into cracks and other openings in rocks. When the water freezes it expands, pushing large blocks of rock away from the main mountain mass. In polar deserts and other regions affected by frost wedging, large talus slopes may form adjacent to mountain fronts, and these are prone to frequent rock falls from frost wedging.

LOESS

Loess, silt and clay deposited by wind, forms a uniform blanket that covers hills and valleys at many altitudes, distinguishing it from deposits of streams. Strong winds that blow across desert regions sometimes pick up dust made of silt and clay particles and transport them thousands of miles (thousands of km) from their source. For instance, dust from China is found in Hawaii, and the Sahara Desert commonly drops dust in Europe. This dust is a nuisance, has a significant influence on global climate, and has at times, as in the dust bowl days of the 1930s, been known nearly to block out the Sun.

Recently scientists have recognized that wind-blown dust contributes significantly to global climate. Dust storms that come out of the Sahara can be carried around the world and partially block out some of the Sun's radiation. The dust particles may also act as nuclei for raindrops to form around, perhaps acting as a natural cloud-seeding phenomenon. One interesting point to ponder is that as global warming increases global temperatures, the amount and intensity of storms increase, and some of the world's deserts expand. Dust storms may reduce global temperatures and increase precipitation. In this way dust storms may be some kind of self-regulating mechanism whereby the Earth moderates its own climate.

DESERT LANDFORMS

Desert landforms are some of the most beautiful on Earth, often presenting bizarre sculpted mountains, steep walled canyons, and regional gravel plains. They can also be some of the most hazardous landscapes on the planet. The regolith, or mixture of soil and altered bedrock in deserts is thin, discontinuous, and much coarser-grained than in moist regions, and is produced predominantly by mechanical weathering. Chemical weathering is only of minor importance because of the rare moisture. Also the coarse size of particles produced by mechanical weathering causes steep slopes, eroded from steep cliffs and escarpments.

Much of the regolith that sits in deserts is coated with a dark layer of manganese and iron oxides, known as desert varnish, produced by a combination of microorganism activity and chemical reactions with fine manganese dust that settles from the wind.

DESERT DRAINAGE SYSTEMS

Most streams in deserts evaporate before they reach the sea. Most are dry for long periods of time and subject to flash floods during brief but intense rains. These flash floods transport most of the sediment in deserts and form fan-shaped deposits of sand, gravel, and boulders found at the bases of many mountains in desert regions. These flash floods also erode deep, steep-walled canyons through the upstream mountain regions, which is the source of the boulders and cobbles found on the mountain fronts. Intermountain areas in deserts typically have finer-grained material, deposited by slower-moving currents that represent the waning stages of floods as they expand into open areas between mountains after they escape out of mountain canyons.

Flash floods can be particularly hazardous in desert environments, especially when the floods are the result of distant rains. More people die in deserts from drowning in flash floods than die from thirst or dehydration. In many cases rain in faraway mountains occurs while people in downstream areas are not aware it is raining upstream. Rain in deserts is typically a brief but intense thunderstorm, which can drop a couple of inches (> 5 cm) of rain in a short time. The water may then quickly move downstream as a wall of water in mountain canyons, sweeping away all loose material in its path. People or vehicles caught in such a flood are likely to be swept away by the swiftly moving torrent.

Saguaro cactus in Arizona desert *(Paul B. Moore, from Shutterstock, Inc.)*

Dry lake beds in low-lying flat areas, which may contain water only once every few years, characterize many deserts. These playas, or hardpans, typically have deposits of white salts that formed when water from storms evaporated, leaving the lakes dry. There are more than 100 playas in the American southwest, including Lake Bonneville, which formed during the last ice age and now covers parts of Utah, Nevada, and Idaho. When there is water in these basins, they are known as playa lakes. Playas are flat surfaces that make excellent racetracks and runways. The U.S. space shuttles commonly land on Rogers Lake playa at Edwards Air Force Base in California.

Alluvial fans are coarse-grained deposits of alluvium that accumulate at the fronts of mountain canyons. Alluvial fans are very common in deserts, where they are composed of both alluvium and debris-flow deposits. Alluvial fans are quite important for people in deserts, because they are porous and permeable and they contain large deposits of groundwater. In many places alluvial fans so dominate the land surface that they form a *bajada,* or slope, along the base of the mountain range, formed by fans that have coalesced to form a continuous broad alluvial apron.

Pediments represent different kinds of desert surfaces. They are surfaces sloping away from the base of a highland and are covered by a thin or discontinuous layer of alluvium and rock fragments. These erosional features are formed by running water and are typically cut by shallow channels. Pediments grow as mountains are eroded.

Inselbergs are steep-sided mountains or ridges that rise abruptly out of adjacent, monotonously flat plains in deserts. Ayres Rock in central Australia is perhaps the world's best-known inselberg. These are produced by differential erosion, leaving behind as a mountain rocks that for some reason are more resistant to erosion.

WIND IN DESERTS

Wind plays a significant role in the evolution of desert landscapes. Wind erodes in two basic ways. Deflation is a process whereby wind removes material from an area, reducing the land surface. The process is akin to deflating a balloon below the surface of the ground, hence its name. Abrasion is a different process that occurs when particles of sand and other size grains are blown by the wind and impact one another. Exposed surfaces in deserts are subjected to frequent abrasion, which is similar to sandblasting.

Yardangs are elongate (several miles [kms] long), streamlined wind-eroded ridges that resemble an overturned ship's hull sticking out of the water. These unusual features are formed by abrasion, by long-term sand blasting along specific corridors. The sandblasting leaves erosionally resistant ridges but removes the softer material, which itself will contribute to sandblasting in the downwind direction and eventually to the formation of sand, silt, and dust deposits.

Deflation is important on a large scale in places where there is no vegetation. In some places wind has excavated large basins known as deflation basins. Deflation basins are common in the United States from Texas to Canada, as elongate depressions, typically only 3–10 feet (1–3 m) deep. In some places like the Sahara, however, deflation basins may be as many as several hundred feet (100 m) deep.

Deflation by wind can move only small particles away from the source, since the size of the particle that can be lifted is limited by the strength of the wind, which rarely exceeds a few tens of miles per hour (~50 km/h). Deflation therefore leaves boulders, cobbles, and other large particles behind. These get concentrated on the surface of deflation basins and other surfaces in deserts, leaving a surface concentrated in boulders known as desert pavement.

Desert pavements are a long-term, stable desert surface and are not particularly hazardous. When the desert pavement is broken, however, for instance, by being driven across, the coarse cobbles and pebbles get pushed beneath the surface and the underlying sands get exposed to wind action again. Driving across a desert pavement can raise a considerable amount of sand and dust, and if many vehicles drive across the surface, then it can be destroyed and the whole surface becomes active.

A striking, large-scale example of this process was provided by events in the Gulf War of 1991. After Iraq invaded Kuwait in 1990, U.S. and allied forces massed hundreds of thousands of troops on the Saudi Arabian side of the border with Iraq and Kuwait and eventually mounted a multipronged counterattack on Kuwait City that led to its liberation. Several of the prongs circled far to the north then turned around and returned southward to Kuwait City. These prongs took many thousands of heavy tanks, artillery, and other vehicles across a region of stable desert pavement, and the weight of these military vehicles destroyed the pavement to free Kuwait. Since the liberation, the steady winds from the northwest have continued, and this area that was once stable desert pavement and stable dune surfaces (covered with desert pavement and minor vegetation) has been remobilized. Large sand dunes have now formed from the sand previously trapped under the pavement. Other dunes that were stable have been reactivated. Now Kuwait City residents are bracing for what they call the second invasion of Kuwait, but this time the invading force is sand and dust, not a foreign army.

Several measures have been considered to try to stabilize the newly migrating dunes. One is to try to reestablish the desert pavement by spreading cobbles across the surface, but this is unrealistic because of the large area involved. Another proposition, being tested, is to spray petroleum on the migrating dunes to effectively create a blacktop or tarred surface that would be stable in the wind. This is feasible in oil-rich Kuwait but not particularly environmentally friendly.

In China's Gobi and Taklimakan Deserts a different technique to stabilize dunes has proven rather successful. Bales of hay are initially placed in a grid pattern near the base of the windward side of dunes, which decreases the velocity of the air flowing over the dune and reduces the transportation of sand grains over the slip surface. Drought-resistant vegetation is planted between the several-foot (1-m) wide units of hay bales, and then when the dune is more stabilized, vegetation is planted along the dune crest. China is applying this technique across much of the Gobi and Taklimakan Deserts, protecting railways and roads. In northeastern China this technique is being applied in an attempt to reclaim lands that became desert through human activity, and the Chinese are constructing a 5,700-mile (9,000-km) long line of hay bales and drought-resistant vegetation. China is said to be building a new "Green Wall" that will be longer than the famous Great Wall of China, and will, the Chinese hope, prove more effective at keeping out invading forces (in this case, sand) from Mongolia.

WINDBLOWN SAND AND DUST

Most people think of deserts as areas with lots of big sand dunes and continual swirling winds of dust storms. But really dunes and dust storms are not as common as depicted in popular movies, and rocky deserts are more common than sandy deserts. For instance, only about 20 percent of the Sahara is covered by sand; the rest is covered by rocky, pebbly, or gravel surfaces. Sand dunes are locally very important in deserts, however, and wind is one of the most important processes in shaping deserts worldwide. Shifting sands are one of the most severe geologic hazards of deserts. In many deserts and desert border areas the sands are moving into inhabited areas, covering farmlands, villages, and other useful land with thick accumulations of sand. This is a global problem, as deserts are currently expanding worldwide. The Institute of Desert Research in Lanzhou, China, recently estimated that in China alone, 950 square miles (2,460.5 km^2) are encroached on by migrating sand dunes from the Gobi Desert each year, costing the country $6.7 billion per year and affecting the lives of 400 million people.

Wind moves sand by saltation, in arced paths, in a series of bounces or jumps. The surface of dunes on beaches or deserts is typically covered by a thin moving layer of sand particles that are bouncing and rolling along it in this process of saltation.

Wind typically sorts different sizes of sedimentary particles, forming small elongate ridges known as sand ripples, very similar to ripples found in streams. Sand dunes are larger than ripples, up to 1,500 (~450 m) feet high, made of mounds or ridges of sand deposited by wind. These may form where an obstacle distorts or obstructs the flow of air, or they may move freely across much of a desert surface. Dunes have many different forms, but all are asymmetrical. They have a gentle slope that faces into the wind and a steep face that faces away from the wind. Sand particles move by saltation up the windward side, and fall out near the top where the pocket of low-velocity air cannot hold the sand anymore. The sand avalanches, or slips down the leeward slope, known as the slip face. This keeps the slope at the angle of repose, 30–34°. The asymmetry of old dunes indicates the directions ancient winds blew.

The steady movement of sand from one side of the dune to the other causes the whole dune to migrate slowly downwind, typically about 80–100 feet (28–30 m) per year, burying houses, farmlands, temples, and entire towns. Rates of dune migration of up to 350 feet (107 m) per year have been measured in the Western Desert of Egypt and the Ningxia Autonomous Region of China.

A combination of many different factors leads to the formation of very different types of dunes, each with a distinctive shape, potential for movement, and hazards. The main variables that determine a dune's shape are the amount of sand available for transportation, the strength (and directional uniformity) of the wind, and the amount of vegetation that covers the surface. If there is a lot of vegetation and little wind, no dunes will form. In contrast, if there is very little vegetation, a lot of sand, and moderate wind strength (conditions that might be found on a beach), then a group of dunes known as transverse dunes form, with the dune crests aligned at right angles to the dominant wind.

Barchan dunes have crescent shapes and horns pointing downwind; they form on flat deserts with steady winds and a limited sand supply. Parabolic dunes have a U-shape with the U facing upwind. These form where there is significant vegetation that pins the tails of migrating transverse dunes, with the dune being warped into a wide U-shape. These dunes look broadly similar to barchans, except the tails point in the opposite direction. They can be distinguished because, in both cases, the steep side of the dune points away from the dominant wind direction.

Linear dunes are long, straight, ridge-shaped dunes that elongate parallel to the wind direction. These occur in deserts with little sand supply and strong, slightly variable winds. Star dunes form isolated or irregular hills where the wind directions are irregular.

Strong winds that blow across desert regions sometimes pick up dust made of silt and clay particles and transport it thousands of miles (kilometers) from their source. For instance, dust from China is found on Pacific islands, and the Sahara commonly drops dust in southern Europe. This dust is a nuisance, has a significant influence on global climate, and has at times, as in the dust bowl days of the 1930s, been known nearly to block out the sun.

Loess is the name for silt and clay deposited by wind. It forms a uniform blanket that covers hills and valleys at many altitudes, which distinguishes it from deposits of streams. In Shaanxi Province, China, an earthquake that killed 830,000 in 1556 had such a high death toll in part because the inhabitants of the region built their homes out of loess. The loess formed an easily excavated material that hundreds of thousands of villagers cut homes into, essentially living in caves. When the earthquake struck, the loess proved to be a poor building material, and large-scale collapse of the fine-grained loess was directly responsible for most of the high death toll.

Recently it has been recognized that windblown dust contributes significantly to global climate. Dust storms that come out of the Sahara can be carried around the world and partially block some of the sun's radiation. The dust particles may also act as small nuclei for raindrops to form around, perhaps acting as a natural cloud-seeding phenomenon. One interesting phenomenon to consider is that as global warming increases global temperatures, the amount and intensity of storms increase, and some of the world's deserts expand. Dust storms may counter this effect and reduce global temperatures, and increase precipitation.

THE SAHARA

The Sahara is the world's largest desert, covering 5,400,000 square miles (8,600,000 km^2) in northern Africa, including Mauritania, Morocco, Algeria, Tunisia, Libya, Egypt, Sudan, Chad, Niger, and Mali. The desert is bordered on the north and northwest by the Mediterranean Sea and Atlas Mountains, on the west by the Atlantic Ocean, and on the east by the Nile River. But the Sahara is part of a larger arid zone that continues eastward into the Eastern Desert of Egypt and Nubian Desert of Sudan, the Rub' al-Khali of Arabia, and the Lut, Tar, Dasht-I-Kavir, Takla Makan, and Gobi Deserts of Asia. Some classifications include the Eastern and Nubian Deserts as part of the Sahara and call the region of the Sahara west of the Nile the Libyan Desert, whereas other classifications consider them separate entities. The southern border of the Sahara is less well defined, but is generally taken as about 16° latitude where the desert grades into transitional climates of the Sahel steppe.

Rocky- and stone- or gravel-covered denuded plateaus known as hammada cover about 70 percent of the Sahara, and sand dunes cover about 15 percent. High mountains, rare oases, and transitional regions occupy the remaining 15 percent. Major mountain ranges in the eastern Sahara include the uplifted margins of the Red Sea that form steep escarpments dropping more than 6,000 feet (2,000 m) from the Arabian Desert into the Red Sea coastal plain. Rocks in these mountains include predominantly Precambrian granitic gneisses, metasediments, and mafic schists of the Arabian shield, and are rich in mineral deposits, including especially gold that has been exploited by the Egyptians since Pharaonic times. The highest point in the Sahara is Emi Koussi in Chad, which rises to 10,860 feet (3,415 m), and the lowest point is the Qattara Depression in the northwest Desert of Egypt.

High, isolated mountain massifs rise from the plains in the central Sahara, including the massive Ahagger (Hogger) in southern Algeria, Tibesti in northern Chad, and Azbine (Air Mountains) in northern Niger. Ahagger rises to more than 9,000 feet (2,740 m) and includes a variety of Precambrian crystalline rocks of the Ouzzalian Archean craton and surrounding Proterozoic Shield. The Air Mountains, rising to more than 6,000 feet (1,830 m), are geologically a southern extension of the Ahagger to the north, containing metamorphosed Precambrian basement rocks. Tibesti rises to more than 11,000 feet (3,350 m) and also includes a core of Precambrian basement rocks, surrounded by Paleozoic and younger cover. Northeast of Tibesti near the Egypt-Libya-Sudan border, the lower Oweineat (Uwaynat) Mountains form a similar dome, rising to 6,150 feet (1,934 m), and have a core of Precambrian igneous rocks.

The climate in the Sahara is among the harshest on the planet, falling in the trade wind belt of dry descending air from Hadley circulation, with strong constant winds blowing from the northeast. These winds have formed elongate linear dunes in specific corridors across parts of the Sahara, with individual sand dunes continuous for hundreds of miles, and virtually no interdune sands. These linear dunes reach heights of more than 1,100 feet (350 m) and may migrate tens of feet (a couple of meters) or more per year. When viewed on a continental scale (as from space or on a satellite image) these linear dunes display a curved trace, formed by the Coriolis force deflecting the winds and sand to the right of the movement direction (northeast to southwest). Most parts of the Sahara receive an average of fewer than five inches (12 cm) of rain a year, and this typically comes in a single downpour every few years, with torrential rains causing flash flooding. Rains of this type run off quickly, and relatively little is captured and returned to the groundwater system for future use. The air is extremely dry, with typical relative humidities ranging from 4 percent to 30 percent. Temperatures can be extremely hot, and the diurnal variation is high. The world's highest recorded temperature is from the Libyan Desert, 136°F (58°C) in the shade, during fall 1922. The temperature drop at night can be up to 90°F (30°C), even dropping below freezing after a scorching hot day.

Most of the Sahara is sparsely vegetated, with shrub brushes being common, along with grasses, and trees in the mountains. Some desert oases and sections along the Nile River are extremely lush, however, and the Nile valley has extensive agricultural development. Animal life is diverse, including gazelles, antelopes, jackals, badgers, hyenas, hares, gerbils, sheep, fox, wild ass, weasel, baboon, mongoose, and hundreds of species of birds.

A variety of minerals are exploited from the Sahara, including major deposits of iron ore from Algeria, Mauritania, Egypt, Tunisia, Morocco, and Niger. Uranium deposits are found throughout the Sahara, with large quantities in Morocco. Manganese is mined in Algeria, and copper is found in Mauritania. Oil is exported from Algeria, Libya, and Egypt.

Vast groundwater reservoirs underlie much of the Sahara, both in shallow alluvial aquifers and in fractured bedrock aquifers. The water in these aquifers fell as rain thousands of years ago, reflecting a time when the climate over North Africa was much different. In the Pleistocene much of the Sahara experienced a wet, warm climate, and more than 20 large lakes covered parts of the region. The region experienced several alternations between wet and dry climates in the past couple of hundred thousand years, and active research projects aim to correlate these climate shifts with global events such as glacial and interglacial periods, sea surface and current changes (such as the El Niño–Southern Oscillation). The implications for understanding these changes is enormous, with millions of people affected by expansion of the Sahara, and undiscovered groundwater resources that could be used to sustain agriculture and save populations from decimation. Many of the present drainage and wadi networks in the Sahara follow a drainage network established during the Pleistocene. In the Pliocene the Mediterranean shoreline was about 60 miles (40 km) south of its present location, when sea levels were about 300 feet (100 m) higher than today. Sand sheets and dunes, which are currently moving southward, have been active for only the past few thousand years. These are known to form local barriers to wadi channels in the Sahara, Sinai, and Negev Deserts, and locally block wadis.

The sand of the Sahara and adjacent Northern Sinai probably originated by fluvial erosion of rocks in the uplands to the south, and was transported from south to north by paleo-rivers during wetter climate times, then redistributed by wind. Dry climates such as the present, and low sea levels during glacial maxima, exposed the sediment to wind action that reshaped the fluvial deposits into dunes, whose form depended on the amount of available sand and prevailing wind directions. This hypothesis was developed to suggest the presence of a drainage network to transport fluvial sediments. Indeed, numerous channels incise into the limestone plateau of the central and northern Sahara, and many lead to elongate areas that have silt deposits. Several of these deposits have freshwater fauna and are interpreted as paleolakes and long-standing slack water deposits from floods.

Plio-Pleistocene lakebed sediments have also been identified in many places in the mountains in the Sahara, where erosionally resistant dikes that formed dams in steep-walled bedrock canyons controlled the lakes. The paleolake sediments consist of silts and clays interbedded with sands and gravels, cut by channel deposits. These types of lake beds were formed in a more humid Late Plio-Pleistocene climate, based on fossil roots and their continuity with wadi terraces of that age.

The fluvial history of the region reflects earlier periods of greater effective moisture, as is evident also from archaeological sites associated with remnants of travertines and playa or lake deposits. An Early Holocene pluvial cycle is well documented by archaeological investigations at Neolithic playa sites in Egypt. Late Pleistocene lake deposits with associated early and middle Paleolithic archaeological sites are best known from work in the Bir Tarfawi area of southwest Egypt. Similar associations occur in northwest Sudan and Libya.

An extensive network of sand-buried river and stream channels in the eastern Sahara appears on shuttle-imaging radar images. Calcium carbonate associated with some of these buried river channels is thought to have precipitated in the upper zone of saturation during pluvial episodes, when water tables were high. As documented by radiocarbon dating and archaeological investigations, the eastern Sahara experienced a period of greater effective moisture during Early and Middle Holocene time, about 10–5 thousand years ago. Uranium-series dating of lacustrine carbonates from several localities indicated that five paleolake-forming episodes occurred at about 320–250, 240–190, 155–120, 90–65, and 10–5 thousand years ago. These five pluvial episodes correlate with major interglacial stages.

These results support the contention that past pluvial episodes in North Africa correspond to the interglacial periods. Isotopic dating results and field relationships suggest that the oldest lake- and groundwater-deposited carbonates were more extensive than those of the younger period, and the carbonates of the late wet periods were geographically localized within depressions and buried channels.

This archaeological evidence of previous human habitation, coupled with remains of fauna and flora, suggests the presence of surface water in the past. Remains of lakes and segments of dry river and stream channels occur throughout the Sahara. Archaeological evidence of human habitation during the Early Holocene was recently uncovered in the northeast Sinai Peninsula where an Early Middle Paleolithic site shows evidence for habitation at 33,800 years before present (BP).

ATACAMA DESERT

The Atacama Desert is an elevated arid region located in northern Chile, extending more than 384 square miles (1,000 km^2) south from the border with Peru. The desert is located 2,000 feet (600 m) above sea level and is characterized by numerous dry salt basins (playas), flanked on the east by the Andes and on the west by the Pacific coastal range. The Atacama is the driest place on Earth, with no rain ever recorded in many areas, and practically no vegetation. Nitrate and copper are mined extensively in the region.

The Atacama is first known to be crossed by the Spanish conquistador Diego de Almagro in 1537, but was ignored until the middle 19th century, when mining of nitrates in the desert began. After World War I, however, synthetic nitrates were developed and the region has experienced economic decline.

GOBI DESERT

One of the world's great deserts, the Gobi is located in central Asia encompassing more than 500,000 square miles (1,295,000 km^2) in Mongolia and northern China. The desert covers the region from the Great Khingan Mountains northwest of Beijing to the Tien Shan north of Tibet, but the desert is expanding at an alarming rate, threatening the livelihood of tens of thousands of farmers and nomadic sheepherders every year. Every spring dust from the Gobi covers eastern China, Korea, and Japan, and may extend at times around the world. Northwesterly winds have removed almost all the soil from land in the Gobi, depositing it as thick loess in eastern China. Most of the Gobi is situated on a high plateau resting 3,000 to 5,000 feet (900–1,500 m) above sea level, and it contains numerous alkaline sabkhas and sandy plains in the west. Regions in the Gobi include abundant steppes, high mountains, forests, and sandy plains. The Gobi has yielded many archaeological, paleontological, and geological finds, including early stone implements, dinosaur eggs, and mineral deposits and precious stones including turquoise and jasper.

NAMIB DESERT AND THE SKELETON COAST

Namibia's Atlantic coastline is known as the skeleton coast, named for the suffering and death that beset many sailors attempting to navigate the difficult waters swept by the cold Benguela current, which moves along the coast, and warm winds coming off the Namib and Kalahari Deserts. The coastline is littered with numerous shipwrecks, testifying to the difficult and often unpredictable nature of shifting winds and ocean currents. Giant sand dunes of the Namib sand sea reach to the coast, and in places these dunes are also covered in bones of mammals that have searched in vain for water. Many dune types are present, including transverse dunes and barchans, and the winds in the region often cause a steady moan to grow from the blowing sands. The desert elephant lives in the region, eating and drinking in generally dry, inland riverbeds, but sometimes venturing to the harsh coast. Oryx, giraffe, hyena, springbok, ostrich, rare rhinos, and lions also roam the area, whereas Cape fur seals populate parts of the coast. Whales and dolphins swim along the coast, and occasionally, giant whale skeletons are washed up and exposed on the shore.

The cold Benguela current breaks off from the circum-Antarctica cold current and forms a cold sea breeze that often shrouds the region in mist and fog, especially during winter months. This mist sustains an unusual plant life in the desert and forms an additional navigational hazard for ships.

DRY VALLEYS OF ANTARCTICA

The Dry Valleys are the largest area on Antarctica not covered by ice. Approximately 98 percent of the continent is covered by ice, but the Dry Valleys, located near McMurdo Sound on the side of the continent closest to New Zealand, have a cold desert climate and receive only four inches (10 cm) of precipitation per year, overwhelmingly in the form of snow. The Dry Valleys are one of the coldest, driest places on Earth and are used by researchers from NASA as an analog for conditions on Mars. No vegetation grows in the Dry Valleys, although a number of unusual microbes live in the frozen soils and form cyanobacterial mats in places. In the Southern Hemisphere summer, glaciers in the surrounding Transantarctic Mountains release significant quantities of meltwater so that streams and lakes form over the thick permafrost in the valleys.

See also ARABIAN GEOLOGY; ASIAN GEOLOGY; ATMOSPHERE; CLIMATE; CLIMATE CHANGE.

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Devonian The Devonian is the fourth geological period in the Paleozoic Era, spanning the interval from 408 to 360 million years ago. It was named after exposures in Devonshire in southwest England. British geologists Adam Sedgwick (1785–1873) and Roderick I. Murchison (1792–1871) first described the Devonian in detail in 1839. The Devonian is divided into three series and seven stages based on its marine fauna.

Devonian rocks are known from all continents and reflect the distribution of the continents grouped into a large remnant Gondwanan fragment in the Southern Hemisphere, and parts of Laurasia (North America and Europe), Angaraland (Siberia), China, and Kazakhstania in the Northern Hemisphere. The eastern coast of North America and adjacent Europe experienced the Acadian orogeny, formed in response to subduction and eventual collision between Avalonian fragments and ultimately Africa with Laurasia. Other orogenies affected North China, Kazakstania, and other fragments. These mountain-building events shed large clastic wedges, including the Catskill delta in North America and the Old Red sandstone in the British Isles.

The Devonian experienced several eustatic sea-level changes and had times of glaciation. There was a strong climatic gradation with tropical and monsoonal conditions in equatorial regions, and cold water conditions in more polar regions.

Marine life in the Devonian was prolific, with brachiopods reaching their peak. Rugose and tabulate corals, stromatoporoids, and algae built carbonate reefs in many parts of the world including North America, China, Europe, North Africa, and Australia. Crinoids, trilobites, ostracods, and a variety of bivalves lived around the reefs and in other shallow water environments, whereas calcareous foraminifera and large ammonites proliferated in the pelagic

Middle Devonian coral reef construction, including different metazoans such as the coelenterates *(Tom McHugh/Photo Researchers, Inc.)*

realm. The pelagic conodonts peaked in the Devonian, and their great variety, widespread distribution, and rapid changes make them useful biostratigraphic markers and form the basis for much of the biostratigraphic division of Devonian time. Bony fish evolved in the Devonian and evolved into tetrapod amphibia by the end of the period.

The land was inhabited by primitive plants in the Early Devonian, but by the middle of the period great swampy forests with giant fern trees (*Archaeopteris*) and spore-bearing plants populated the land. Insects, including some flying varieties, inhabited these swamps.

The end of the Devonian brought widespread mass extinction of some marine animal communities, including brachiopods, trilobites, conodonts, and corals. The cause of this extinction is not well known, with models including cooling caused by a southern glaciation, or a meteorite impact.

The Devonian saw the climactic development of the Appalachian Mountain belt in eastern North America. The Appalachians extend for 1,600 miles (1,000 km) along the east coast of North America, stretching from the St. Lawrence River valley in Quebec Canada, to Alabama. Many classifications consider the Appalachians to continue through Newfoundland in maritime Canada, and before the Atlantic Ocean opened, the Appalachians were continuous with the Caledonides of Europe. Home to many of America's great universities, the Appalachians are one of the best-studied mountain ranges in the world, and understanding of their evolution was one of the factors that led to the development and refinement of the paradigm of plate tectonics in the early 1970s.

Rocks that form the Appalachians include those that were deposited on or adjacent to North America and thrust on the continent during several orogenic events. For the length of the Appalachians, the older continental crust consists of Grenville Province gneisses, deformed and metamorphosed about 1 billion years ago during the Grenville orogeny. The Appalachians grew in several stages. After Late Precambrian rifting, the Iapetus Ocean evolved and hosted island arc growth, while a passive margin sequence was deposited on the North American rifted margin in Cambrian-Ordovician times. In the Middle Ordovician the collision of an island arc terrane with North America marks the Taconic orogeny, followed by the Mid-Devonian Acadian orogeny, which probably represents the collision of North America with Avalonia, off the coast of Gondwana. This orogeny formed huge molassic fan delta complexes of the Catskill Mountains, and was followed by strike-slip faulting. The Late Paleozoic Alleghenian orogeny formed striking folds and faults in the southern Appalachians, but was dominated by strike-slip faulting in the Northern Appalachians. This event appears to be related to the rotation of Africa to close the remaining part of the open ocean in the southern Appalachians. Late Triassic-Jurassic rifting reopened the Appalachians, forming the present Atlantic Ocean.

See also North American geology; Paleozoic.

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Dewey, John F. (1937–) British *Tectonicist, Structural Geologist* John F. Dewey is regarded as one of the founders of the modern plate tectonic paradigm and one of the earliest scientists to apply the plate tectonic model to ancient mountain belts such as the Appalachians. He is also well known for his pioneering work on plate kinematics and using principles of plate kinematics on a sphere to understand complex geological problems. After helping to offer explanations of the Appalachian Mountain belt in terms of plate tectonics, Dewey later expanded his studies to a global scale. He presented plate tectonic concepts in a kinematic framework, clearly describing many phenomena for the first time.

John Dewey grew up in London during World War II, and excelled in athletics, especially boxing, rugby, cricket, gymnastics, high jump, and javelin. Although he was good at sports, he realized he could not make a profession out of it, and when he turned 16 he found another passion—geology. Dewey was inspired by his great uncle, Henry Dewey, a British government geologist, and he convinced his housemaster at Bancroft's School (Essex, United Kingdom) to let him pursue geology as a career. The headmaster at his school, John Hayward, was also an amateur geologist and encouraged Dewey in his studies, which eventually led to Dewey's receiving a first-class degree in geology from Queen Mary's College, University of London, in 1957. He next received a Ph.D. in geology from the University of London in 1960. After this Dewey turned down many opportunities for careers in the oil and mining industry, deciding instead to pursue an academic career, taking a job as a lecturer at the University of Manchester, then at the Cambridge University.

In the late 1960s the field of geology entered a revolution with the new theory of plate tectonics. Dewey was fascinated by the developments and in 1967 took a three-month sabbatical position at the Lamont Geological Observatory in New York City, where he studied the Appalachian/Caledonian mountain belt and began to apply the principles of plate tectonics to this ancient orogenic belt. While seeing the plate tectonic and kinematic model develop, in part from his colleagues at Lamont, Dewey became one of the early pioneers to apply the same principles to old mountain belts, using the Appalachian-Caledonian belt as the prime example. Dewey and his colleagues John Bird and, later, Kevin Burke recognized that the Appalachians and other mountain belts preserved a history of ocean opening and closing, a cycle they termed the Wilson Cycle, after the Canadian geologist J. Tuzo Wilson, one of the pioneers of the plate tectonic model in the oceans. Dewey stayed in America, taking a position at the State University of New York at Albany, where he remained until the mid-1980s. During that time the university became one of the world's leading research institutions for plate tectonics and its applications to old mountain belts, with numerous faculty and students studying the Appalachians, Alps, Himalayas, Andes, Asia, and Precambrian mountain belts of the world.

After 12 years in Albany Dewey moved back to England to become chair of the department of geological sciences at Durham, then moved to become chair of the earth sciences at the University of Oxford. Finally, he left the old society geological network in England and accepted the position of professor of geology at the University of California at Davis in 2001. He was inducted as a member of the National Academy of Sciences in 2005.

Dewey's basic interests and knowledge remain structural geology and tectonics, from the small-scale materials science of deformed rocks to the large-scale origin of topography and structures. Some of his ongoing field-based research is on the rock fabrics and structures of transpression and transtension, especially in California, New Zealand, Norway, Ireland, and Newfoundland. Evolving interests include the neotectonics of California and Nevada and the relationship between faulting, topography, and sediment provenance, yield, and distribution. Derivative interests are the geohazards of volcanoes, earthquakes, and landslides.

See also continental drift; North American geology; plate tectonics.

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diagenesis

Diagenesis is a group of physical and chemical processes that affect sediments after they are deposited but before they undergo deformation and metamorphism. Diagenesis occurs under low temperature (T) and pressure (P) conditions, with its upper PT limit defined as when the first metamorphic minerals appear. Diagenesis typically changes the sediment from a loose, unconsolidated state to a rock that is cemented, lithified, or indurated.

The style of diagenetic changes in sediments is controlled by several factors other than pressure and temperature, including grain size, rate of deposition, sediment composition, environment of deposition, nature of pore fluids, porosity and permeability, and types of surrounding rocks. One of the most important diagenetic processes is dewatering, or the expulsion of water from the pore spaces by the weight of overlying, newly deposited sediments. These waters may escape to the surface or enter other nearby, more porous sediments, where they can precipitate or dissolve soluble minerals. Compaction and dewatering of sediments cause reduction of the thickness of the sedimentary pile. For instance, many muds may contain 80 percent water when they are deposited and compaction rearranges the packing of the constituent mineral grains to reduce the water-filled pore spaces to about 10 percent of the rock. This process results in the clay minerals' being aligned, forming a bedding-plane parallel layering known as fissility. Organic sediments also experience large amounts of compaction during dewatering, whereas other types of sediments including sands may experience only limited compaction. Sands typically are deposited with about 50 percent porosity, and they may retain about 30 percent even after deep burial. The porosity of sandstone is reduced by the pressing of small grains into the pore spaces between larger grains, and the addition of cement.

Chemical processes during diagenesis are largely controlled by the nature of the pore fluids. Fluids may dissolve or more commonly add material to the pore spaces in the sediment, increasing or decreasing pore space, respectively. These chemical changes may occur in the marine realm or in the continental realm with freshwater in the pore spaces. Chemical diagnetic processes tend to be more effective at the higher PT end of the diagenetic spectrum, when minerals are more reactive and soluble.

Organic material experiences special types of diagenesis, as bacteria aid in the breakdown of the organic sediments to form kerogen and release methane and carbon dioxide gas. At higher diagenetic temperatures kerogen breaks down to yield oil and liquid gas. Humus and peat are progressively changed into soft brown coal, hard brown coal, then bituminous coal during the diagenetic process of coalification. This increases the carbon content of the coal and releases methane gas in the process.

Most sandstones and coarse-grained siliciclastic sediments experience few visible changes during diagenesis, but they may experience the breakdown of feldspars to clay minerals and see an overall reduction in pore spaces. The pore spaces in sandstones may become filled with cements such as calcite, quartz, or other minerals. Cements can form at several times in the diagenetic process. Carbonates are susceptible to diagenetic changes and typically see early and late cements, and many are altered by processes such as replacement by silica, dolomitization, and the transformation of aragonite to calcite. Carbonates normally show an interaction of physical and chemical processes, with the weight of overlying sediments forming pressure solution surfaces known as stylolites, where grains are dissolved against one another. These stylolites have characteristic crinkly or wavy surfaces oriented parallel to bedding. The material dissolved along the stylolites is then taken in solution and expelled from the system or, more commonly, reprecipitated as calcite or quartz veins, often at high angles to the stylolites reflecting the stresses induced by the weight of the overburden.

See also HYDROCARBONS AND FOSSIL FUELS; METAMORPHISM AND METAMORPHIC ROCKS; STRUCTURAL GEOLOGY.

divergent plate margin processes

Divergent plate margins occur where two tectonic plates are moving apart from each other. The world's longest mountain chain is the midocean ridge system, extending 25,000 miles (40,000 km) around the planet. The midocean ridge system represents places where two oceanic plates are moving apart or diverging, and new material is moving up from the mantle to form new oceanic crust and lithosphere in the space created by the divergence. These midocean ridge systems are mature extensional boundaries, many of which began as immature extensional boundaries in continents, known as continental rifts. Some continental rift systems are linked to the world rift system in the oceans and are actively breaking continents into pieces. An example is the Red Sea-East African rift system. Other continental rifts are accommodating small amounts of extension in the crust and may never evolve into oceanic rifts. Examples of where this type of rifting occurs on a large scale include the Basin and Range Province of the western United States and Lake Baikal in Siberia, Russia.

DIFFERENT STYLES OF EXTENSION AT DIVERGENT PLATE BOUNDARIES

Although divergent boundaries are all similar in that they are places where the crust and entire lithosphere are breaking and moving apart, there are large differences in the processes that allow this extension to occur. Some of these different processes act in different places, while others may work together to produce the extension and associated sinking (subsidence) of the land surface. There are three main end-member models for the mechanisms of extension and subsidence in continental rifts. These are the pure shear model, the simple shear model, and the dike injection model.

In the pure shear model for extension, the lithosphere thins symmetrically about the rift axis, being pulled apart like taffy at depth and along brittle faults near the surface. The base of the lithosphere (defined by the 2,425°F [1,330°C] isotherm, or line of equal temperature) rises to 10–20 miles (15–30 km) below the surface near the center of the rift axis but remains at normal depths of 75 miles (120 km) away from the rift. This causes high heat flow and high temperature gradients with depth (geothermal gradients) in rifts, and is consistent with many measurements of the strength of the Earth's gravity force that suggest an excess mass at depth (this would correspond to the denser asthenosphere near the surface). Stretching mechanisms in the pure shear model include brittle accommodation of stretching on faults near the surface. At about four miles (7 km) depth, the rocks no longer deform by fracturing but begin to flow like silly putty—a transition known as the brittle ductile transition—and extension below this depth is accommodated by shear on ductile shear zones.

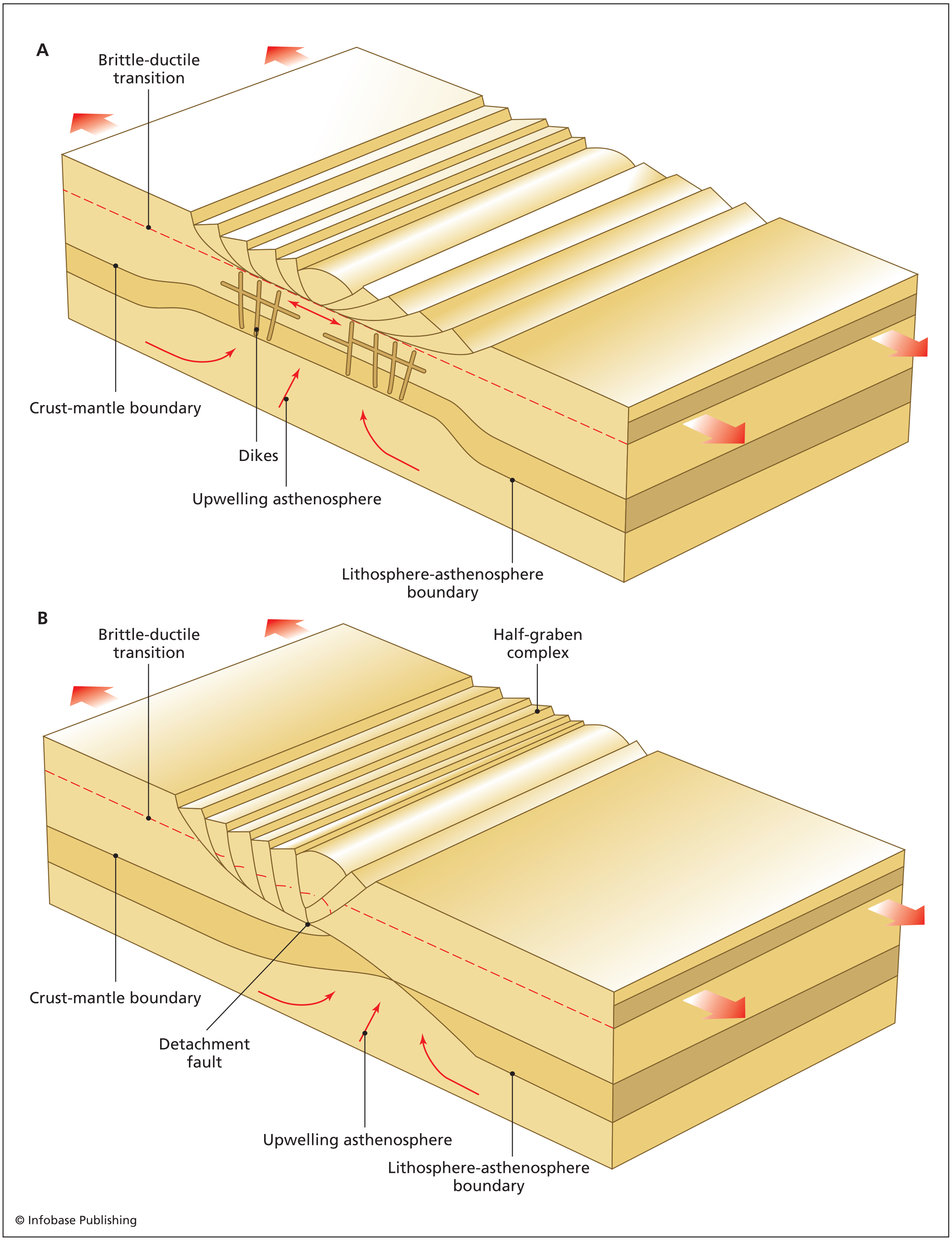
In the simple shear model for extension, an asymmetric fault known as a detachment fault penetrates the thickness of the lithosphere, dipping a few degrees, forming a system of asymmetric structures across the rift. A series of rotated fault blocks may form where the detachment is close to the surface, whereas the opposite side of the rift (where the lithosphere experiences the most thinning) may be dominated by the eruption of volcanic rocks. Heating of the crust associated with the lithospheric thinning typically causes the upward doming of the detachment fault, and since the heating (and uplift) is greatest in a region offset from the center of the rifting zone, the center of the uplifted dome tends to be located on one side of the rift. This model explains differences on either side of rifts, such as faulted and volcanic margins now on opposite continental margins (conjugate margins) of former rifts that have evolved into oceans. A good example of where this can be observed is along the Red Sea of the Middle East, where many volcanic rocks are located on the Arabian side of the sea, and few are found on the African side of the rift.

The dike injection model for extension in rifts suggests that a large number of dense igneous dikes (with basaltic composition) intrude the continental lithosphere in rifts, causing the lithosphere to become denser and to sink or subside. This mechanism does not really explain most aspects of rifts, but it may contribute to the total amount of subsidence in the other two models.

In all of these models for initial extension of the rift, initial geothermal gradients (how the temperature changes with depth) are raised and the temperatures become elevated and compressed beneath the rift axis. After the initial stretching and subsidence phases, the rift either becomes inactive or evolves into a midocean ridge system. In the latter case the initial shoulders of the rift become passive continental margins. Failed rifts and passive continental margins both enter a second, slower phase of subsidence related to the gradual recovery of the isotherms (lines of equal temperature) to their deeper, prerifting levels. This process takes about 60 million years and typically forms a broad basin over the initial rifts, characterized by no active faults, no volcanism, and rare lakes. The transition from initial stretching with coarse clastic sediments and volcanics to the thermal subsidence phase is commonly called the "rift to drift" transition on passive margins.

DIVERGENT PLATE BOUNDARIES IN CONTINENTS

Rifts are elongate depressions formed where the entire thickness of the lithosphere has ruptured in extension. In these places the continents are beginning to break apart as immature divergent boundaries, and if successful, may form new ocean basins. The general geomorphic feature that initially forms is known as a rift valley. Rift valleys have steep, fault-bounded sides, with rift shoulders that typically tilt slightly away from the rift valley floor. Drainage systems tend to be short, internal systems, with streams forming on the steep sides of the rift, flowing along the rift axis, and draining into deep, narrow lakes within the rift. If the rift is in an arid



Modes of extension in rifts. (A) Shows pure shear model, in which the lithosphere extends symmetrically and asthenosphere rises to fill the space vacated by the extending lithosphere. (B) Shows simple shear or asymmetric rifting, where a shallow-dipping detachment fault penetrates the thickness of the lithosphere, and asthenosphere rises asymmetrically on the side of the rift where the fault enters the asthenosphere. Faulting patterns are also asymmetric, with different styles on either side of the rift.

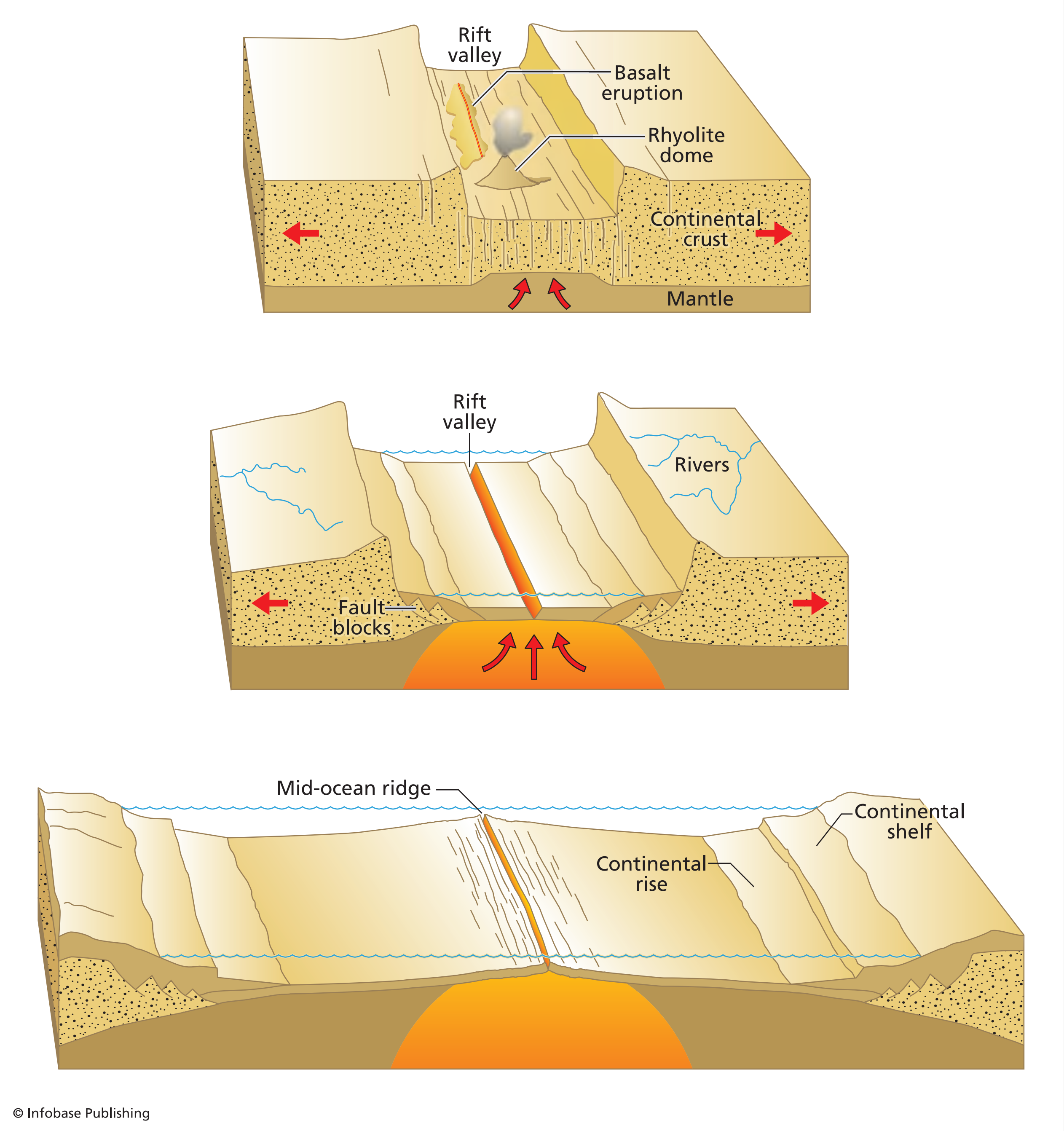


Figure showing simplified three-stage evolution of divergent margins. The young rift valley stage like that in the East African rift system has steep rift shoulders and basaltic and rhyolitic volcanoes. The young ocean stage, similar to the modern Red Sea, has seafloor spreading and steep rift shoulders. Mature ocean stage is like the modern Atlantic Ocean, with thick passive margin sequences developed on continental edges around a wide ocean basin.

environment, such as much of East Africa, the drainage may have no outlet and the water will evaporate before it can reach the sea. This process leaves distinctive deposits of salts and other minerals that form by being left behind during evaporation of seawater (evaporites), one of the hallmark deposits of continental rift settings. Other types of deposits in rifts include lake sediments in rift centers, and conglomerates (cemented gravels) derived from rocks exposed along the rift shoulders. These sediments may be interleaved with volcanic rocks, typically alkaline (having abundant sodium, Na, and other alkali elements) and bimodal in silica content (i.e., basalts and rhyolites).

DIVERGENT PLATE BOUNDARIES IN THE OCEANS: THE MIDOCEAN RIDGE SYSTEM

Some continental rifts may evolve into midocean ridge-spreading centers. The world's best example of where this transition can be observed is in the Ethiopian Afar, where the East African continental rift system meets juvenile oceanic spreading centers in the Red Sea and Gulf of Aden. Three plate boundaries meet in a wide plate boundary zone in the Afar, including the African/Arabian boundary (Red Sea spreading center), the Arabian/Somalian boundary (Gulf of Aden spreading center), and the African/Somalian boundary (East African rift). The boundary is a complex system known as an RRR (rift-rift-rift) triple junction. The triple junction has many complex extensional structures, with most of the Afar near sea level, and isolated blocks of continental crust such as the Danakil horst isolated from the rest of the continental crust by normal faults.

The Red Sea has a young, or juvenile, spreading center similar in some aspects to the spreading center in the middle of the Atlantic Ocean. Geologists recognize two main classes of oceanic spreading centers, based on characteristics of the shapes of their surfaces (geomorphology) and elevation or topography. These different types are formed in spreading centers with different spreading rates, with slow spreading rates, 0.2–0.8 inches per year (0.5–2 cm/yr), on Atlantic-type ridges, and faster rates, generally 1.5–3.5 inches per year (4–9 cm/yr), on Pacific-type ridges.

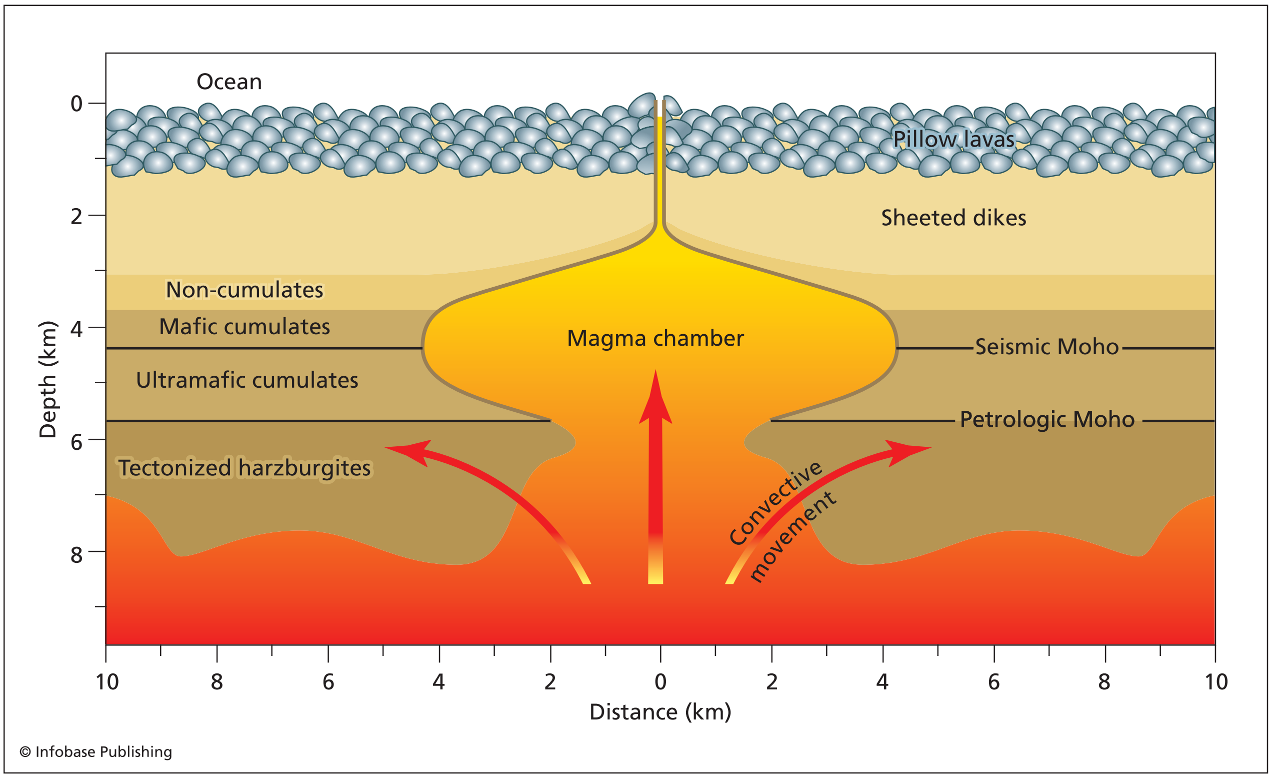
Atlantic-type ridges are characterized by a broad, 900–2,000-mile (1,500–3,000-km) wide swell in which the seafloor rises 0.6–1.8 miles (1–3 km) from abyssal plains at 2.5 miles (4.0 km) below sea level to about 1.7 miles (2.8 km) below sea level along the ridge axis. Slopes on the ridge are generally less than 1°. Slow, or Atlantic-type, ridges have a median rift, typically about 20 miles (30 km) wide at the top to 0.6–2.5 miles (1–4 km) wide at the bottom of the long, deep medial rift. Many constructional volcanoes are located along the base and inner wall of the medial rift. Rugged topography and many faults forming a strongly block-faulted slope characterize the central part of Atlantic-type ridges.

Pacific-type ridges are generally 1,250–2,500 miles (2,000–4,000 km) wide, and rise 1.2–1.8 miles (2–3 km) above the abyssal plains, with 0.1° slopes. Pacific-type ridges have no median valley but many shallow earthquakes, high heat flow, and low gravity in the center of the ridge, suggesting that magma may be present at shallow levels beneath the surface. Pacific-type ridges have much smoother flanks than Atlantic-type ridges.

The high topography of both types of ridges shows that they are underlain by low-density material and are floating on this hot substrate. Geologists call this mechanism of making mountains isostatic compensation. New magma upwells beneath the ridges and forms small magma chambers along the ridge axis. The magma in these chambers crystallizes to form the rocks of the oceanic crust that gets added (in approximately equal proportions) to both diverging plates. The crust formed at the ridges is young, hot, and relatively light, so it floats on the hot underlying asthenosphere. As the crust ages and moves away from the ridge, it becomes thicker and denser, and subsides; this explains the topographic profile of the ridges. The rate of thermal subsidence is the same for fast- and slow-spreading ridges (a function of the square root of the age of the crust), explaining why slow-spreading ridges are narrower than fast-spreading ridges.

Abundant volcanoes, with vast outpourings of basaltic lava, characterize the centers of the midocean ridges. The lavas are typically bulbous-shaped forms called pillows, as well as tubes and other, more massive flows. The ridge axes are also characterized by high heat flow, with many thermal vents marking places where seawater has infiltrated the oceanic crust and made its way to deeper levels, where it is heated by coming close to the magma, then rises again to vent on the seafloor. Many of these vents precipitate sulfide and other minerals in great quantities, forming chimneys called black smokers that may be many tens of feet (several meters) tall. These chimneys have high-temperature metal- and nutrient-rich water flowing out of them (at temperatures of several hundred degrees Celsius), with the metals precipitating once the temperature drops on contact with the cold seawater outside the vent. These systems may cover parts of the oceanic crust with layers of sulfide minerals. Unusual primitive communities of sulfide-reducing bacteria, tube worms, and crabs have been found near several black smoker vents along midocean ridges. Many scientists believe that similar settings may have played an important role in the early appearance and evolution of life on the planet.

Geophysical seismic refraction studies in the 1940s and 1950s established that the oceanic crust exhibits seismic layering similar in many places in the oceans. Seismic layer one consists of sediments, layer two is interpreted to be a layer of basalt 0.6–1.5 miles (1–2.5 km) thick, and layer three is approximately four miles (6 km) thick and interpreted to be crystal cumulates, underlain by the mantle. Some ridges and transform faults expose deeper levels of the oceanic lithosphere. These typically include a mafic dike complex, thick sections of gabbro, and ultramafic cumulates. In some places rocks of the mantle are exposed, typically consisting of strongly deformed ultramafic rocks that have had a large amount of



Formation of oceanic crust and lithosphere at midocean ridges. Magma forms by partial melting in the asthenosphere and upwells to make a magma chamber beneath the ridge axis. As the plates move apart, dikes intrude upward from the magma chamber and feed the lava flows on the surface. Heavy crystals settle out of the magma chamber and form layers of crystal cumulates on the magma chamber floor.

magma squeezed out of them. These unusual rocks are called depleted harzburgite tectonites.

As the plates move apart, the pressure on deep underlying rocks is lowered, which causes them to rise and partially melt by 15–25 percent. Basaltic magma is produced by partially melting the peridotitic mantle, leaving a residue-type of rock in the mantle known as harzburgite. The magma produced in this way moves up from deep within the mantle to fill the gap opened by the diverging plates. This magma forms a chamber of molten or partially molten rock that slowly crystallizes to form a coarse-grained igneous rock known as gabbro, which has the same composition as basalt. Before crystallization some of the magma moves up to the surface through a series of dikes and forms the crustal-sheeted dike complex, and basaltic flows. Many of the basaltic flows have distinctive forms, with the magma forming bulbous lobes known as pillow lavas. Lava tubes are also common, as are fragmented pillows formed by the inward explosive collapse (implosion) of the lava tubes and pillows. Back in the magma chamber other crystals grow in the gabbroic magma, including olivine and pyroxene, and are heavier than the magma, so they sink to the bottom of the chamber. These crystals form layers of dense minerals known as cumulates. Beneath the cumulates the mantle material from which the magma was derived becomes progressively more deformed as the plates diverge and form a highly deformed ultramafic rock known as a harzburgite or mantle tectonite. This process can be seen on the surface in Iceland along the Reykjanes Ridge.

Much of the detailed information about the deep structure of oceanic crust comes from the study of ophiolites, which are interpreted to be on-land equivalents of oceanic crust tectonically emplaced on the continents during the process of convergent tectonics and ocean closure. Studies of ophiolites have confirmed the general structure of the oceanic crust as inferred from the seismic reflection and refraction studies and limited drilling. Numerous detailed studies of ophiolites have allowed unprecedented detail about the structure and chemistry of inferred oceanic crust and lithosphere to be completed, and as many variations as similarities have been discovered. The causes of these variations are numerous, including differences in spreading rate, magma supply, temperature, depth of melting, tectonic setting (arc, forearc, back arc, midocean ridge, etc.), and the presence or absence of water. The ocean floor, however, is still largely unexplored, and scientists know more about many other planetary surfaces than is known about Earth's ocean floor.

The mid-Atlantic ridge rises above sea level on the North Atlantic island of Iceland, lying 178 miles (287 km) off the coast of Greenland and 495 miles (800 km) from the coast of Scotland. Iceland has an average elevation of more than 1,600 feet (500 m) and owes its elevation to a hot spot that is interacting with the midocean ridge system beneath the island. The mid-Atlantic ridge crosses the island from southwest to northeast, and has a spreading rate of 1.2 inches per year (3 cm/yr), with the mean extension oriented toward an azimuth of 103°. The oceanic Reykjanes ridge and sinistral transform south of the island rises to the surface and continues as the Western Rift Zone. Active spreading is transferred to the Southern Volcanic Zone across a transform fault called the South Iceland Seismic Zone, then continues north through the Eastern Rift Zone. Spreading is offset from the oceanic Kolbeinsey ridge by the dextral Tjornes fracture zone off the island's northern coast.

During the past 6 million years the Iceland hot spot has drifted toward the southeast relative to the North Atlantic, and the oceanic ridge system has made a succession of small jumps so that active spreading has remained coincident with the plume of hottest and therefore weakest mantle material. These ridge jumps have caused the active spreading to propagate into regions of older crust that have been remelted, forming unusual alkalic and even silicic volcanic rocks that are deposited unconformably over older oceanic (tholeiitic) basalts. Active spreading occurs along a series of 5–60 mile (10–100 km) long zones of fissures, graben, and dike swarms, with basaltic and rhyolitic volcanoes rising from central parts of fissures. Hydrothermal activity is intense along the fracture zones, with diffuse faulting and volcanic activity merging into a narrow zone within a few miles beneath the surface. Detailed geophysical studies have shown that magma episodically rises from depth into magma chambers located a few miles below the surface, then dikes intrude the overlying crust and flow horizontally for tens of miles to accommodate crustal extension of several to several tens of feet over several hundred years.

Many Holocene volcanic events are known from Iceland, including 17 eruptions of Hekla from the Southern Volcanic zone. Iceland has an extensive system of glaciers and has experienced a number of eruptions beneath them that cause water to infiltrate the fracture zones. The mixture of water and magma induces explosive events including Plinian eruption clouds, phreo-magmatic, tephra-producing eruptions, and sudden floods known as jokulhlaups induced when the glacier experiences rapid melting from contact with magma. Many Icelanders have learned to use the high geothermal gradients to extract geothermal energy for heating and to enjoy the many hot springs on the island.

See also AFRICAN GEOLOGY; CONVERGENT PLATE MARGIN PROCESSES; PLATE TECTONICS; TRANSFORM PLATE MARGIN PROCESSES.

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drainage basin (drainage system) The total area that contributes water to a stream is called a drainage basin, and the line that divides different drainage basins is known as a divide (such as the continental divide) or interfluve. Drainage basins are the primary landscape units, or systems, concerned with the collection and movement of water and sediment into streams and river channels. They consist of a number of interrelated systems that work together to control the distribution and flow of water within the basin. Hillslope processes, bedrock and surficial geology, vegetation, climate, and many other systems all interact in complex ways that determine where streams will form and how much water and sediment they will transport. A drainage basin's hydrologic dynamics can be analyzed by considering these systems along with how much water enters the basin through precipitation and how much leaves the basin in the discharge of the main trunk channel. Streams are arranged in an orderly fashion in drainage basins, with progressively smaller channels branching away from the main trunk channel. Stream channels are ordered and numbered according to this systematic branching. The smallest segments lack tributaries and are known as first-order streams; second-order streams form where two first-order streams converge, third-order streams form where two second-order streams converge, and so on.

Streams within drainage basins develop characteristic branching patterns that reflect, to some degree, the underlying bedrock geology, structure, and rock types. Dendritic or randomly branching patterns form on horizontal strata or on rocks with uniform erosional resistance. Parallel drainage patterns develop on steeply dipping strata, or on areas with systems of parallel faults or other landforms. Trellis drainage patterns consist of parallel main-stream channels intersected at nearly right angles by tributaries, in turn fed by tributaries parallel to the main channels. Trellis drainage patterns reflect significant structural control and typically form where eroded edges of alternating soft and hard layers are tilted, as in folded mountains or uplifted coastal strata. Rectangular drainage patterns form a regular rectangular grid on the surface and typically form in areas where the bedrock is strongly faulted or jointed. Radial and annular patterns develop on domes, including volcanoes and other roughly circular uplifts. Other, more complex patterns are possible in more complex situations.

Several categories of streams in drainage basins reflect different geologic histories—a consequent stream is one whose course is determined by the direction of the slope of the land. A subsequent stream is one whose course has become adjusted so that it occupies a belt of weak rock or another geologic structure. An antecedent stream has maintained its course across topography that is being uplifted by tectonic forces; these cross high ridges. Superposed streams' courses were laid down in overlying strata onto unlike strata below. Stream capture occurs when headland erosion diverts one stream and its drainage into another drainage basin.

See also ESTUARY; FLUVIAL; GEOMORPHOLOGY; RIVER SYSTEM.

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Du Toit, Alexander (1878–1948) South African *Geologist* Alexander Du Toit, known as "the world's greatest field geologist," was an early supporter of the theory of continental drift proposed by German meteorologist Alfred Wegener. Du Toit is credited with extensive mapping of the rocks sequences deposited on the Gondwana supercontinent and was one of the first scientists to knowledgeably correlate sequences between different continents.

Alexander Du Toit was born on March 14, 1878, near Cape Town and attended school at a local diocesan college in Rondebosch and at the University of the Cape of Good Hope. He then spent two years studying mining engineering at the Royal Technical College in Glasgow, United Kingdom, graduating in 1899, and then moved to study geology at the Royal College of Science in London before returning to study surveying and mining in Glasgow. In 1901 he was a lecturer at the Royal Technical College and at the University of Glasgow. He returned to South Africa in 1903, joining the Geological Commission of the Cape of Good Hope, and spent the next several years constantly in the field doing geological mapping. This time in his life was the foundation for his extensive understanding and unrivaled knowledge of South African geology. During his first season he worked with South African geologist Arthur W. Rogers in the western Karoo, where they established the stratigraphy of the Lower and Middle Karoo System. They also recorded the systematic phase changes in the Karoo and Cape Systems. Along with these studies they mapped the dolerite intrusives, their acid phases, and their metamorphic aureoles, publishing numerous papers on the subject. Throughout the years Du Toit worked in many areas including the Stormberg area and the Karoo coal deposits near the Indian Ocean. He was very interested in geomorphology and hydrogeology. The most significant contribution of his work was the theory of continental drift. He was the first to realize that the southern continents had once formed the supercontinent of Gondwana, which was distinctly different from the northern supercontinent Laurasia. In 1927 Du Toit took a position as chief consulting geologist at De Beers Consolidated Mines in South Africa and remained there until he retired in 1941.

Du Toit received many honors and awards. He was the president of the Geological Society of South Africa, a corresponding member of the Geological Society of America, and a member of the Royal Society of London. Some of Du Toit's most famous papers and books that proved influential in the gradual acceptance of the theory of plate tectonics include his *A Geological Comparison of South America with South Africa* (1927) and *Our Wandering Continents,* (1937). In 1933 Du Toit was awarded the Murchison Medal by the Geological Society of London.

See also AFRICAN GEOLOGY; CONTINENTAL DRIFT; GONDWANA, GONDWANALAND; PLATE TECTONICS.

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dwarfs (stars) Stellar evolution is strongly related to the mass and size of a star, with normal stars following a stellar evolution curve called the main sequence. The term *dwarf star* oddly refers to stars whose size is normal for their mass, which lie on the main sequence curve, and which are converting hydrogen to helium by nuclear fusion in their cores. Dwarfs are also classified as any star with a radius comparable to or smaller than the Earth's Sun, which is classified as a yellow dwarf. Other types of dwarf stars are more unusual; these include white dwarfs, which are collapsed but still hot and shining stars; black dwarfs, which are cold, dead stars; and brown dwarfs, which are simply not massive enough to fuse hydrogen in their cores.

White dwarfs are small degenerate stars composed of electron-degenerate matter formed by the compression of electrons to positions close to the atomic nucleus in low-energy quantum states during stellar collapse. They are the end state of normal solar mass stars following the main sequence of stellar evolution. Since white dwarfs have masses about equal to the Sun and sizes about equal to the Earth, they are quite dense, yet are only faintly luminous, with the light coming from stored heat. About 6 percent of stars in the vicinity of the Earth's solar system are known to be white dwarfs, yet most stars (perhaps 97 percent) in the solar system may end up as white dwarfs in the end states of their evolution.

Main-sequence stellar evolution shows that after the hydrogen-fusing stage of stellar evolution, main-sequence stars expand into a red giant that fuses helium to carbon and oxygen in its core. If this red giant has sufficient mass to elevate core temperatures above the limit where it can fuse carbon, then spent carbon and oxygen will build up in the stellar core. This will eventually explode, forming a planetary nebula in which the outer layers of the star are shed and the remaining mass becomes a white dwarf star; this process explains why white dwarfs are rich in carbon and oxygen. Some white dwarfs also contain neon and magnesium.

White dwarfs are dead stars that no longer undergo fusion reactions since they have no source of internal energy. The stars collapse to the point at which the electron degeneration pressure is strong enough to stop the gravitational force from compressing the electrons closer to the atomic nuclei, leaving the atoms in a low-energy quantum state. This condition exists for stars with up to 1.4 solar masses, above which collapse may continue, forming a supernova. When white dwarfs initially form by collapse, they are hot, but they gradually cool by radiational transfer to space. With time white dwarfs cool so much that they are no longer visible; they are then called black dwarfs. Cooling to this point by radioactive processes requires more time than the age of the universe, however, so no black dwarfs yet exist, and they are classified as hypothetical stars.

A different variety of dwarf star is known as a brown dwarf. To generate fusion of hydrogen in the star, it must have started on the main sequence with a mass of at least 80 times that of Jupiter. Any star smaller than that would be hard to detect, because it was never massive enough to generate internal fusion of hydrogen. Still, brown dwarfs have convective surfaces and interiors, and are in an intermediate mass range between giant gaseous planets like Jupiter and true stars. There are two known stars with relative sizes and surface temperatures that classify them as brown dwarfs: Tiede 1 and Gliese 229B. Tiede 1 is similar to a yellow dwarf star like Earth's Sun, whereas Gliese 229B is close to a red dwarf category and is the approximate size of Jupiter. Red dwarfs are at the critical mass required for internal fusion, but present observations make it uncertain whether Gliese 229B is just above or just below that limit.

Red dwarf stars are cool, low-mass stars with less than 40 percent of the mass of the Sun, and are characterized by low-energy generation in their cores and relatively low luminosity. The brightest red dwarf has only about 10 percent of the luminosity of the Sun; thus red dwarfs are hard to detect, even though they may constitute the majority of stars in the solar system. Red dwarfs have hydrogen fusion in their cores and transport heat to their surfaces by convection, but the rate of heat generation is so low that they remain dim. Since convection removes the helium produced by hydrogen fusion in the stars' cores, red dwarfs can burn much of their hydrogen fuel before they leave the main sequence of stellar evolution, and they tend to have long life cycles. Stars as massive as the Earth's Sun accumulate helium in their cores and may live only about 10 billion years, but red dwarfs with about 10 percent of the solar mass may live for as long as 10 trillion years.

After the hydrogen in a red dwarf is mostly consumed, the core begins to contract, generating additional heat by gravitational contraction, which is then transferred to the stellar surface by convection. Eventually red dwarfs cool, fusion and contraction cease, and they fade from view. The closest star to the Earth's Sun is Proxima Centauri, which is a red dwarf.

See also ASTRONOMY; ASTROPHYSICS; COSMOLOGY; STELLAR EVOLUTION.

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E

Earth Earth is the third planet from the center of our solar system, located between Venus and Mars at a distance of 93 million miles (150 × 10^6 km) from the Sun. It has a mean radius of 3,960 miles (6,371 km), a surface area of 2.04 × 10^8 square miles (5.101 × 10^8 km^2), and an average density of 5.5 grams per cubic centimeter. As one of the terrestrial planets (Mercury, Venus, Earth, and Mars), Earth is composed of solid rock, with silicate minerals being the most abundant in the outer layers and a dense iron-nickel alloy forming the core material.

Earth and other planets condensed from a solar nebula about 5 billion years ago. In this process a swirling cloud of hot dust, gas, and protoplanets collided with one another, eventually forming the main planets. The accretion of Earth was a high-temperature process that allowed melting of the early Earth and segregation of the heavier metallic elements such as iron (Fe) and nickel (Ni) to sink to the core, and for the lighter rocky elements to float upward. This process led to the differentiation of Earth into several concentric shells of contrasting density and composition, and was the main control on the large-scale structure of Earth today.

The main shells of Earth include the crust, a light outer shell 3–43 miles (5–70 km) thick. This is followed inward by the mantle, a solid rocky layer extending to 1,802 miles (2,900 km). The outer core is a molten metallic layer extending to 3,170 miles (5,100 km) depth and the inner core is a solid metallic layer extending to 3,958 miles (6,370 km). With the acceptance of plate tectonics in the 1960s, geologists recognized that the outer parts of Earth were also divided into several zones that had very different mechanical properties. The outer shell of Earth was divided into many different rigid plates all moving with respect to each other, with some of them carrying continents in continental drift. This outer rigid layer became known as the lithosphere; it ranges from 45 to 95 miles (75–150 km) thick. The lithosphere is essentially floating on a denser, but partially molten layer of rock in the upper mantle known as the asthenosphere (or weak sphere). The weakness of this layer allows the plates on the surface of Earth to move about.

The most basic division of Earth's surface shows that it is divided into continents and ocean basins, with oceans occupying about 60 percent of the surface and continents 40 percent. Mountains are

Earth seen by *Apollo 17* crew: Africa and Madagascar at center of field of view *(NASA)* elevated portions of the continents. Shorelines are where the land meets the sea, whereas continental shelves are broad to narrow areas underlain by continental crust, covered by shallow water. The shelves drop off to continental slopes, consisting of steep drop-offs from shelf edges to the deep ocean basin, and at the continental rise the slope flattens to merge with the deep-ocean abyssal plains. Ocean ridge systems are subaquatic mountain ranges where seafloor spreading creates new ocean crust. Mountain belts on Earth are of two basic types. Orogenic belts are linear chains of mountains, largely on the continents, that contain highly deformed, contorted rocks that represent places where lithospheric plates have collided or slid past one another. The midocean ridge system is a 40,000-mile (65,000-km) long mountain ridge that represents vast outpourings of young lava on the ocean floor and places where new oceanic crust is being generated by plate tectonics. After it is formed, it moves away from the ridge crests, and new magmatic plates fill the space created by the plates drifting apart. The oceanic basins also contain long, linear, deep-ocean trenches that are up to several kilometers deeper than the surrounding ocean floor and locally reach depths of seven miles (14 km) below the sea surface. These are places where the oceanic crust is sinking back into the mantle of Earth, completing the plate tectonic cycle for oceanic crust.

External layers of Earth include the hydrosphere, consisting of the ocean, lakes, streams, and the atmosphere. The air/water interface is very active, for here erosion breaks rocks down into loose debris—the regolith.

The hydrosphere is a dynamic mass of liquid, continuously on the move, including all the water in oceans, lakes, streams, glaciers, and groundwater, although most water is in the oceans. The hydrologic cycle describes changes, both long- and short-term, in Earth's hydrosphere. It is powered by heat from the Sun, which causes evaporation and transpiration. This water then moves in the atmosphere and precipitates as rain or snow, which then drains off in streams, evaporates, or moves as groundwater, eventually to begin the cycle over and over again.

The atmosphere is the sphere around Earth consisting of the mixture of gases called air. It is hundreds of kilometers thick and is always moving, because more of the Sun's heat is received per unit area at the equator than at the poles. The heated air expands and rises to where it spreads out, cools and sinks, and gradually returns to the equator. The effects of Earth's rotation modify this simple picture of the atmosphere's circulation. The Coriolis effect causes any freely moving body in the Northern Hemisphere to veer to the right and toward the left in the Southern Hemisphere.

The biosphere is the totality of Earth's living matter and partially decomposed dead plants and animals. It is made up largely of the elements carbon, hydrogen, and oxygen. When these organic elements decay, they may become part of the regolith and are returned through geological processes to the lithosphere, atmosphere, or hydrosphere.

See also ATMOSPHERE; BIOSPHERE; ENERGY IN THE EARTH SYSTEM; LITHOSPHERE; MAGNETIC FIELD, MAGNETOSPHERE; MANTLE.

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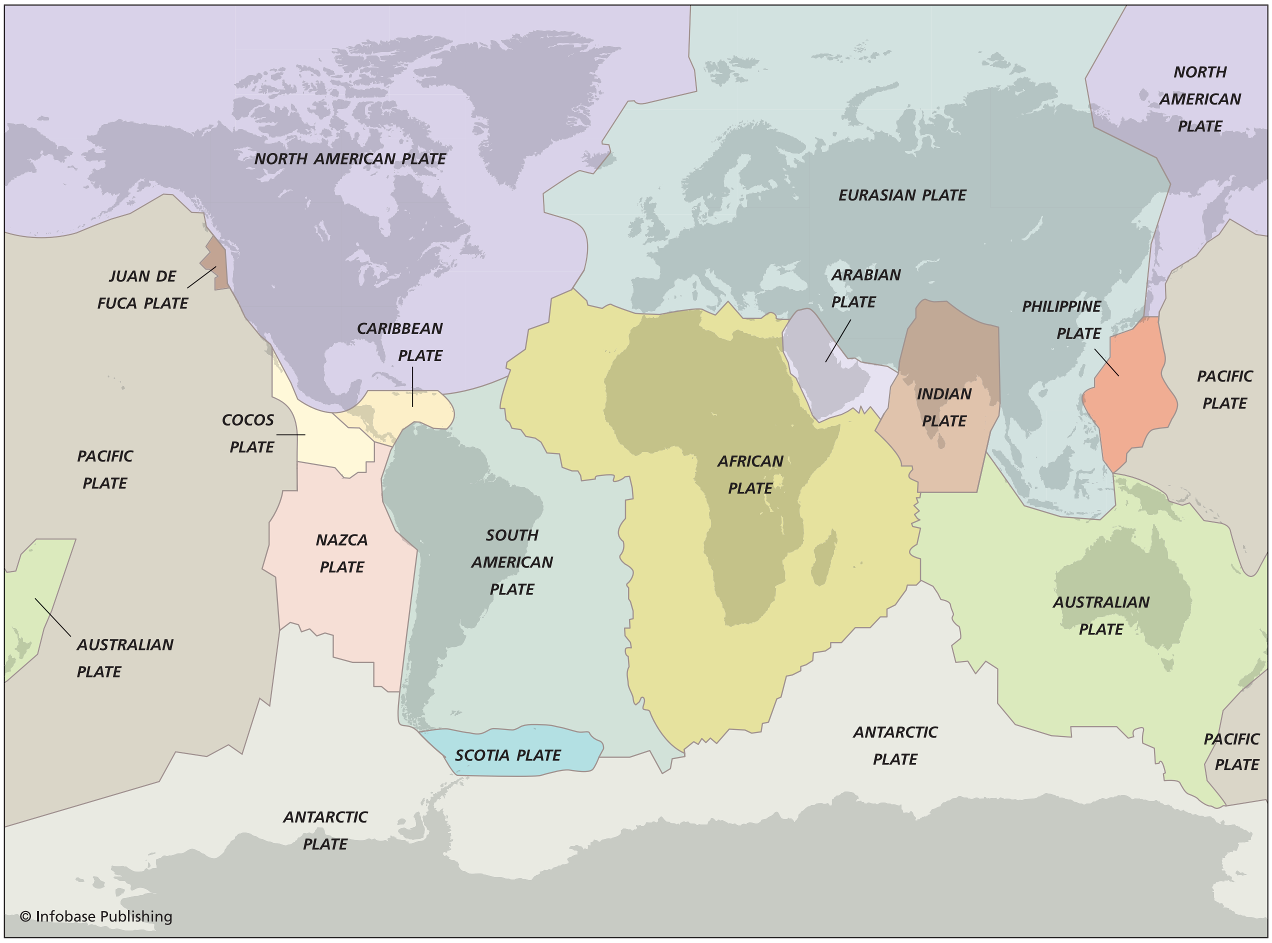
earthquakes An earthquake occurs when a sudden release of energy causes the ground to shake and vibrate, associated with the passage of waves of energy released at the source. Earthquakes can be extremely devastating and costly events, sometimes killing tens or hundreds of thousands and leveling entire cities in a few seconds. A single earthquake may release the energy equivalent to hundreds or thousands of nuclear blasts and may cost billions of dollars in damage, not to mention the toll in human suffering. Earthquakes are also associated with secondary hazards, such as tsunami, landslides, fire, famine, and disease that also exert their toll on humans and other animals.

Most earthquakes occur along plate boundaries. The lithosphere (or outer rigid shell) of the Earth is broken into about 12 large tectonic plates, each moving relative to the others. There are many other smaller plates. Most earthquakes happen where two of these plates meet and are moving past each other, such as in southern California. Recent earthquakes in China, Turkey, Sumatra (Indonesia), and Mexico have also been located along plate boundaries. A map of plate boundaries of the Earth and earthquakes shows where significant earthquakes have occurred in the past 50 years. Most really big earthquakes occur at boundaries where the plates are moving toward each other (as in Alaska and Japan), or sliding past each other (as in southern California and Turkey). Smaller earthquakes occur where the plates are moving apart, such as along midoceanic ridges where new magma rises and forms oceanic spreading centers.

The area that gets the most earthquakes in the continental United Stated is southern California along the San Andreas Fault. The reason for this high number of earthquakes is that the Pacific plate is sliding north relative to the North American plate along the track of the San Andreas fault. The motion in this



Locations of significant earthquakes and plate boundaries. Shallow-focus earthquakes (in pink) are found at all types of plate boundaries; medium- and deep-focus quakes are found along subduction zones.

area is characterized as a "stick-slip" type of sliding, where the two plates stick to each other along the plate boundary as the two plates slowly move past each other, and stresses rise over tens or hundreds of years. Eventually the stresses along the boundary rise so high that the strength of the rocks is exceeded, and the rocks suddenly break, causing the two plates to move dramatically (slip) up to 20–30 feet (5–7 m) in a few seconds. This sudden motion of previously stuck segments along a fault plane is an earthquake. The severity of the earthquake is determined by how large an area breaks in the earthquake, how far it moves, how deep within the Earth the break occurs, and the length of time that the broken or slipped area along the fault takes to move. The elastic-rebound theory states that recoverable (also known as elastic) stresses build up in a material until a specific level or breaking point is reached. When the breaking point or level is attained, the material suddenly breaks, releasing energy and stresses in an earthquake. In the case of earthquakes, rows of fruit trees, fences, roads, and railroad lines that became gradually bent across an active fault line as the stresses built up are typically noticeably offset across faults that have experienced an earthquake. When the earthquake occurs, the rocks snap along the fault, and the bent rows of trees, fences, or roads/rail line become straight again, but displaced across the fault.

Some areas away from active plate boundaries are also occasionally prone to earthquakes. Even though earthquakes in these areas are uncommon, they can be very destructive. Places including Boston, Massachusetts; Charleston, South Carolina; and New Madrid, Missouri (near St. Louis) have been sites of particularly bad earthquakes. In 1811 and 1812 three large earthquakes with magnitudes of 7.3, 7.5, and 7.8 were centered in New Madrid and shook nearly the entire United States, causing widespread destruction. Most buildings were toppled near the origin of the earthquake, and several deaths were reported (the region had a population of only 1,000 at the time, but is now densely populated). Damage to buildings was reported from as far away as Boston and Canada, where chimneys toppled, plaster cracked, and church bells were set to ringing by the shaking of the ground.

Many earthquakes in the past have been incredibly destructive, killing hundreds of thousands, like the ones in Wenchuan, China; Iran; Sumatra, Indonesia, and Mexico City in recent years (see the table below). Some earthquakes have killed nearly a million people, such as one in 1556 in China that killed 800,000–900,000, another in China in 1976 that killed an estimated 242,000 to 800,000 people, one in Calcutta, India, in 1737 that killed about 300,000 people, and the earthquake-related Indian Ocean tsunami that killed an estimated 286,000 people in 2004. The 2008 magnitude 8 Wenchuan earthquake in China has an official death toll of about 90,000, but unofficial estimates reach up to 1,000,000.

ORIGINS OF EARTHQUAKES

Earthquakes can originate from sudden motion along a fault, from a volcanic eruption, bomb blasts, landslides, or anything else that suddenly releases energy on or in the Earth. Not every fault is associated with active earthquakes. Most faults are in fact no longer active but were active at some time in the geologic past. Of the active faults, only some are particularly prone to earthquakes. Some faults are slippery, and the two blocks on either side just slide by each other passively without producing major earthquakes. In other cases, however, the blocks stick together and deform until they reach a certain point at which they suddenly snap, releasing energy in an earthquake event.

Rocks and materials are said to behave in a brittle way when they respond to built-up tectonic pressures by cracking, breaking, or fracturing. Earthquakes represent a sudden brittle response to built-up stress and are almost universally activated in the upper few kilometers of the earth. Deeper than this, the pressure and temperature are so high that the rocks simply deform like silly putty and do not snap, but are said to behave in a ductile manner.

An earthquake originates in one place then spreads out in all directions along the fault plane. The focus is the point in the Earth where the earthquake energy is first released and is the area on one side of a fault that actually moves relative to the rocks on the other side of the fault plane. After the first slip event the area surrounding the focus experiences many smaller earthquakes as the surrounding rocks also slip past one another to even out the deformation caused by the initial earthquake shock. The epicenter is the point on the Earth's surface that lies vertically above the focus.

When big earthquakes occur, the surface of the Earth actually forms into waves that move across the surface, just as in the ocean. These waves can be pretty spectacular and also extremely destructive. When an earthquake strikes, these seismic waves move out in all directions, just like sound waves, or

THE 13 DEADLIEST EARTHQUAKES IN RECORDED HISTORY

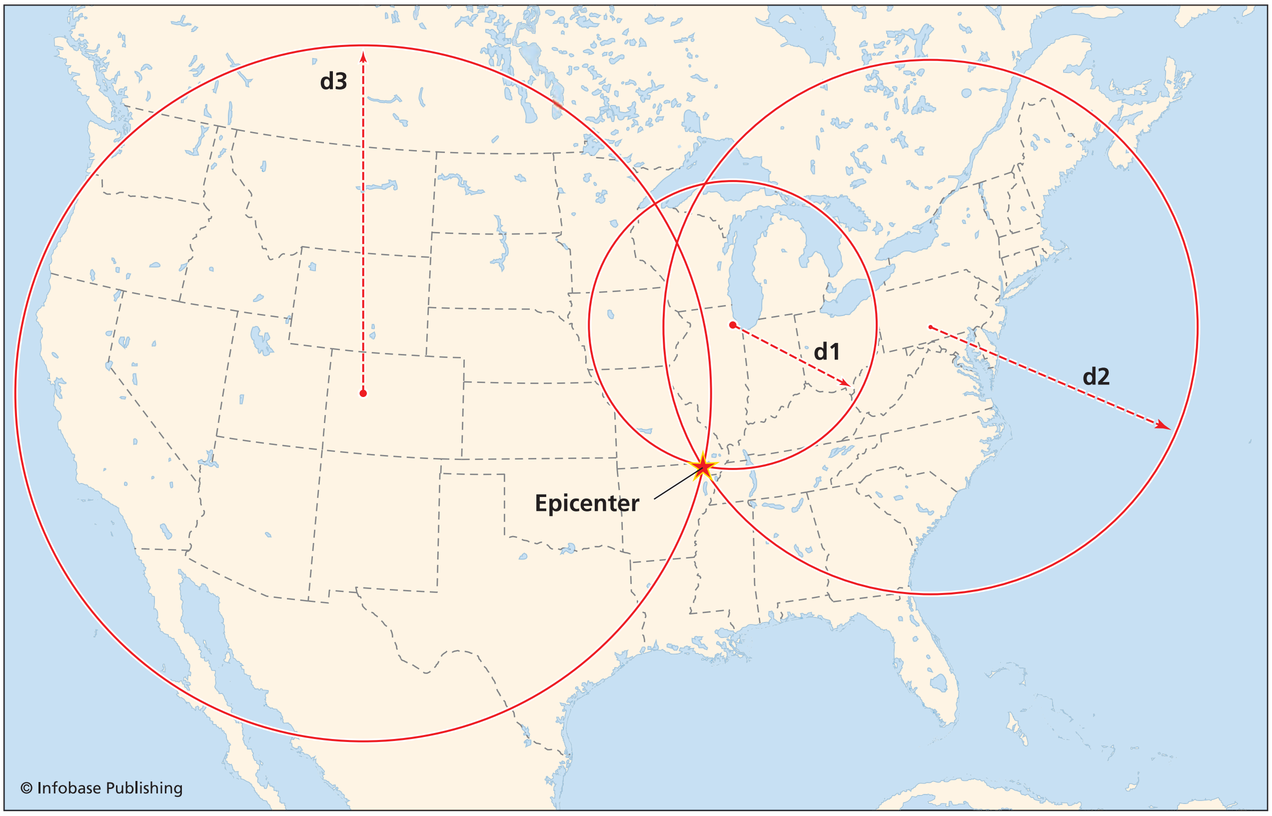
Place	Year	Deaths	Estimated Magnitude
Shaanxi, China	1556	830,000	
Calcutta, India	1737	300,000	
Sumatra, Indonesia	2004	286,000	9.0
T'ang Shan, China	1976	242,000 (could be as many as 800,000)	7.8
Port-au-Prince, Haiti	2010	200,000 (preliminary estimate)	7.0
Gansu, China	1920	180,000	8.6
Messina, Italy	1908	160,000	7.5
Tokyo, Japan	1923	143,000	8.3
Beijing, China	1731	100,000	
Chihli, China	1290	100,000	
Naples, Italy	1693	93,000	
Wenchuan, China	2008	90,000 (could be as many as 1,000,000)	7.9
Gansu, China	1932	70,000	7.6

Note: Casualties from the 2008 Wenchuan earthquake and the 2010 Haiti earthquake were still being tabulated at the time of writing.

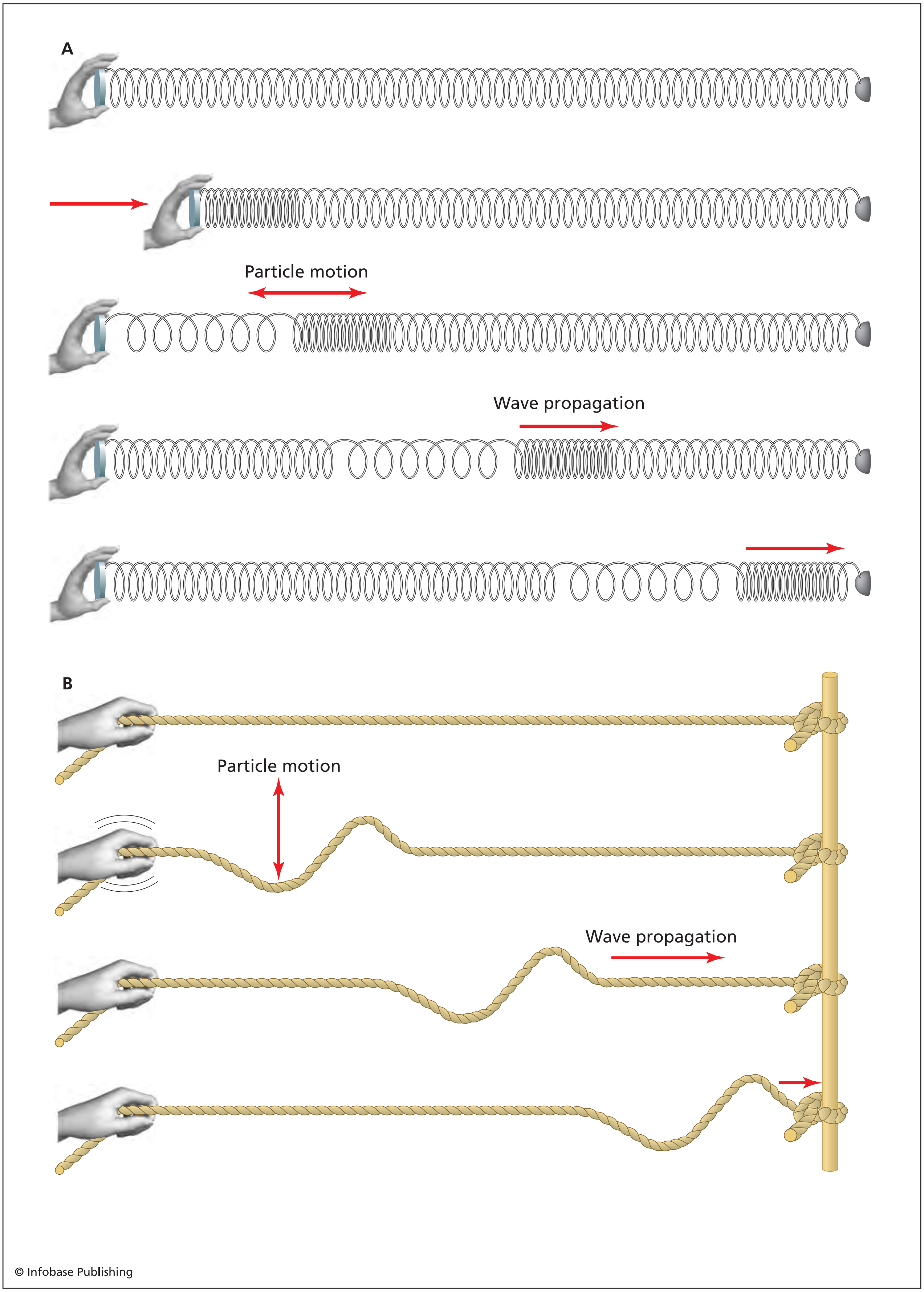
ripples that move across water after a stone is thrown in a still pond. After the seismic waves have passed through the ground, the ground returns to its original shape, although buildings and other human constructions are commonly destroyed. In really large earthquakes the ground is deformed into waves of rock, several feet high (~1 m), moving at very high speeds.

During an earthquake, several types of seismic waves can either radiate underground from the focus—called body waves—or aboveground from the epicenter—called surface waves. The body waves travel through the whole body of the Earth and move faster than surface waves, whereas surface waves cause most of the destruction associated with earthquakes because they briefly change the shape of the surface of the earth when they pass. There are two types of body waves—P (primary or compressional) waves, and S, or secondary waves. P-waves deform material through a change in volume and density, and these can pass through solids, liquids, and gases. The kind of movement associated with the passage of a P-wave is a back-and-forth–type motion. Compressional (P) waves move with high velocity, about 3.5–4 miles per second (6 km/second), and are thus the first to be recorded by seismographs. This is why they are called Primary (P) waves. P-waves cause a lot of damage because they temporarily change the area and volume of ground on which humans have built or modified in ways that require the ground to keep its original shape, area, and volume. When the ground suddenly changes its volume by expanding and contracting, many of these constructions break. For instance, if a gas pipeline is buried in the ground, it may rupture and explode when a P-wave passes because of its inability to change its shape along with the earth. Fires and explosions originating from broken pipelines commonly accompany earthquakes. History has shown that fires often do as much damage after the earthquake as the ground shaking did during the quake. This fact is dramatically illustrated by the 1906 earthquake in San Francisco, where much of the city burned for days after the shaking and was largely destroyed. Similarly, much of the damage and loss of life from the 1995 magnitude 7.3 Kobe, Japan, earthquake was from fires ignited by gas lines and home heating systems.

The second kind of body waves are shear waves (S), or secondary waves, because they change the shape of a material but not its volume. Solids can only transmit shear waves. Shear waves move material at right angles to the direction of wave travel,



Method of locating epicenters by calculating the distance to the source from three different seismic stations. The distance to the epicenter is calculated using the time difference between the first arrivals of P- and S-waves. The unique place that the three distance circles intersect is the location of the epicenter.



Analogy to seismic P- and S-waves using slinky and rope and thus they consist of an alternating series of sideways motions. Holding a jump rope at one end on the ground and moving it rapidly back and forth can simulate this kind of motion. Waves form at the end being held, and they move the rope sideways as they approach toward the loose end of the rope. A typical shear wave velocity is two miles per second (3.5 km/second). These kinds of waves may be responsible for knocking buildings off foundations when they pass, since their rapid sideways or back-and-forth motion is often not met by buildings. The effect is much like pulling a tablecloth out from under a set table—if done rapidly, the building (as is the case for the table setting) may be left relatively intact, but detached from its foundation.

Surface waves can also be extremely destructive during an earthquake. These have complicated types of twisting and circular motions, much like the circular motions one might feel while swimming in waves out past the surf zone at the beach. Surface waves travel more slowly than either type of body wave, but because of their complicated motion they often cause the most damage. This is a good thing to remember during an earthquake, because if one realizes that the body waves have just passed one's location, there may be a brief period of no shaking to go outside before the very destructive surface waves hit and cause even more destruction.

MEASURING EARTHQUAKES

To measure the intensity of shaking during an earthquake, geologists use seismographs, which display earth movements by means of an ink-filled stylus on a continuously turning roll of graph paper. Modern seismographs have digital versions of the same design but record the data directly to computer systems for analysis. When the ground shakes, the needle wiggles and leaves a characteristic zigzag line on the paper. Many seismograph records clearly show the arrival of P- and S-body waves, followed by surface waves.

Seismographs are built according to a few simple principles. To measure the shaking of the Earth during a quake, the point of reference must be free from shaking, ideally on a hovering platform. Since building perpetually hovering platforms is impractical, engineers have designed an instrument known as an inertial seismograph, which makes use of the principle of inertia, the resistance of a large mass to sudden movement. When a heavy weight is hung from a string or thin spring, the string can be shaken and the big heavy weight will remain stationary. Using an inertial seismograph, the ink-filled stylus is attached to the heavy weight and remains stationary during an earthquake. The continuously turning graph paper is attached to the ground and moves back and forth during the quake, recording the zigzag trace of the earthquake motion on the graph paper.

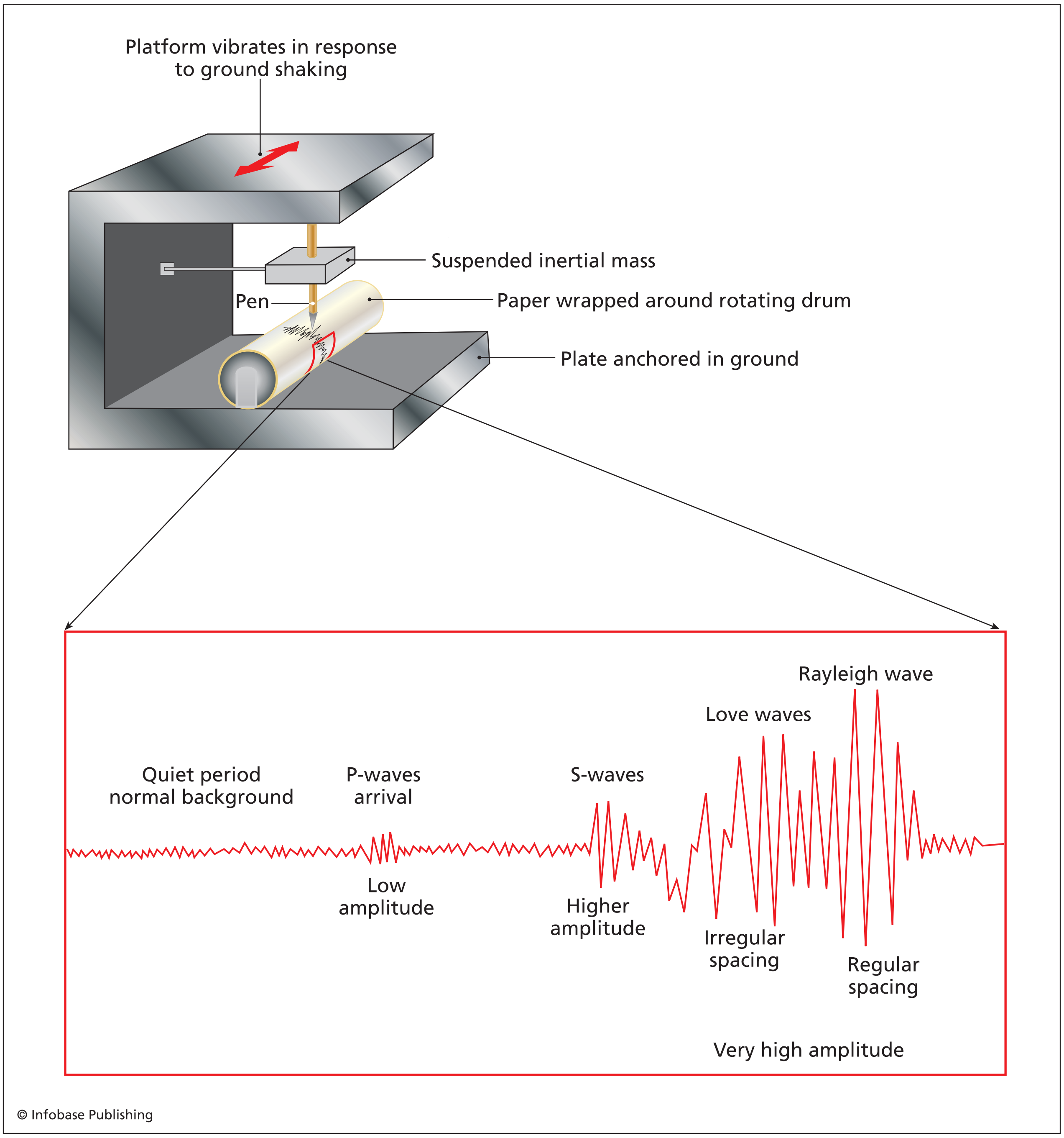
Seismographs are used in series, some set up as pendulums and others as springs, to measure ground motion in many directions. Engineers have made seismographs that can record motions as small as one hundred millionth of an inch, about equivalent to being able to detect the ground motion caused by a car several blocks away. The ground motions recorded by seismographs are very distinctive, and geologists who study them have methods of distinguishing between earthquakes produced along faults, earthquake swarms associated with magma moving into volcanoes, and even between explosions from different types of construction and nuclear blasts. Interpreting seismograph traces has therefore become an important aspect of nuclear test-ban treaty verification. Many seismologists are employed to monitor earthquakes around the world and to verify that countries are not testing nuclear weapons.

EARTHQUAKE MAGNITUDE

Earthquakes vary greatly in intensity, from undetectable ones up to ones that kill millions of people and wreak total destruction. For example, an earthquake in 2008 killed at least 90,000 people in China, yet several thousand earthquakes that do no damage occur every day throughout the world. The energy released in large earthquakes is enormous, up to hundreds of times more powerful than large atomic blasts. Strong earthquakes may produce ground accelerations greater than the force of gravity, enough to uproot trees or send projectiles through buildings, trees, or anything else in their path. Earthquake magnitudes are most commonly measured by the Richter scale.

The Richter scale gives an idea of the amount of energy released during an earthquake. It is based on the amplitudes (half the height from wave-base to wave-crest) of seismic waves at a distance of 61 miles (100 km) from the epicenter. The Richter scale magnitude of an earthquake is calculated by using the zigzag trace produced on a seismograph, once the epicenter has been located by comparing signals from several different, widely separated seismographs. The Richter scale is logarithmic, whereby each step of 1 corresponds to a 10-fold increase in amplitude. This is necessary because the energy of earthquakes changes by factors of more than a hundred million.

The energy released in earthquakes changes even more rapidly with each increase in the Richter scale, because the number of high-amplitude waves increases with bigger earthquakes and also because the energy released is according to the square of the amplitude. Thus it turns out in the end that an



Schematic diagram of an inertial seismograph showing a large inertial mass suspended from a spring. The mass remains stationary as the ground and paper wrapped around a rotating drum move back and forth during an earthquake, creating the seismogram.

increase of 1 on the Richter scale corresponds to a 30-fold increase in energy released. The largest earthquakes so far recorded are the 9.2 Alaskan earthquake (1964), the 9.5 Chilean earthquake (1960), and the 9.0 Sumatra earthquake (2004), each of which released the energy equivalent to more than 10,000 nuclear bombs the size of the one dropped on Hiroshima.

Before the development of modern inertial seismographs, earthquake intensity was commonly measured by the modified Mercalli intensity scale. This scale, named after Giuseppe Mercalli, was developed in the late 1800s; and it measures the amount of vibration people remember feeling for low-magnitude earthquakes, and measures the amount of damage to buildings in high-magnitude events (see table on

MODIFIED MERCALLI INTENSITY SCALE COMPARED WITH RICHTER MAGNITUDE

Mercalli intensity	Richter magnitude	Description
I–II	< 2	Not felt by most people
III	3	Felt by some people indoors, especially on high floors
IV–V	4	Noticed by most people. Hanging objects swing and dishes rattle
VI–VII	5	Everyone feels. Some building damage (esp. to masonry), waves on ponds
VII–VIII	6	Difficult to stand and people scared or panicked. Difficult to steer cars. Moderate damage to buildings
IX–X	7	Major damage, general panic of public. Most masonry and frame structures destroyed. Underground pipes broken. Large landslides
XI–XII	8 and higher	Near total destruction

Note: This table can be used to compare the relative magnitudes of earthquakes from the historical record for which only information on the Mercalli intensity may be known, with the intensity on the modern Richter magnitude scale.

page 232). One of the disadvantages of the Mercalli scale is that it is not corrected for distance from the epicenter. People near the source of the earthquake therefore may measure the earthquake as an IX or X, whereas those farther from the epicenter might record only a I or II event. The modified Mercalli scale, however, has proven useful for estimating the magnitudes of historical earthquakes that occurred before the development of modern seismographs, since the Mercalli magnitude can be estimated from historical records.

EARTHQUAKE HAZARDS

Earthquakes are associated with a wide variety of specific hazards, including primary effects such as ground motion, ground breaks (or faulting), mass wasting, and liquefaction. Secondary and tertiary hazards are indirect effects, caused by events initiated by the earthquake. These may include tsunami in open ocean and bay waters; waves that rock back and forth in enclosed basins, called seiche waves; fires and explosions caused by disruption of utilities and pipelines; and changes in ground level that may disrupt habitats, change groundwater level, displace coastlines, cause loss of jobs, and displace populations. Financial losses to individuals, insurance companies, and businesses can easily soar into the tens of billions of dollars for even moderate-sized earthquakes.

Ground Motion

One of the primary hazards of earthquakes is ground motion caused by the passage of seismic waves through populated areas. The most destructive waves

Collapsed 10-story apartment building in Islamabad, Pakistan, after earthquake October 8, 2005: The building pancaked as one floor fell, thereby causing each lower floor to collapse. *(AP images)*

Damage from ground shaking and landslides in Yingxiu, Sichuan Province, China, from May 12, 2008, magnitude 7.9 earthquake *(T. Kusky)*

are surface waves, which in severe earthquakes may visibly deform the surface of the earth into moving waves. Ground motion is most typically felt as shaking; it causes the familiar rattling of objects off shelves reported from many minor earthquakes. The amount of destruction associated with given amounts of ground motion depends largely on the design and construction of buildings and infrastructure according to specific codes.

The amount of ground motion associated with an earthquake generally increases with the magnitude of the quake but depends also on the nature of the substratum—loose, unconsolidated soil and fill tends to shake more than solid bedrock. The Loma Prieta, California, earthquake (1989) dramatically illustrated this phenomenon where areas built on solid rock vibrated the least (and saw the least destruction), and areas built on loose clays vibrated the most. Much of the Bay Area is built on loose clays and mud, including the Nimitz freeway, which collapsed during the event. The area that saw the worst destruction associated with ground shaking was the Marina district. Even though this area is located far from the earthquake epicenter, it is built on loose, unconsolidated landfill, which shook severely during the earthquake, causing many buildings to collapse and gas lines to rupture, initiating fires. More than twice as much damage from ground shaking during the Loma Prieta earthquake was reported from areas over loose fill or mud than from areas built over solid bedrock. Similar effects were reported from the Mexico City earthquake (1985) because the city is built largely on old lake bed deposits.

Additional variation in the severity of ground motion is noted in the way that different types of bedrock transmit seismic waves. Earthquakes that occur in the western United States generally affect a smaller area than those that occur in the central and eastern parts of the country. This is because the bedrock in the west (California, in particular) is generally much softer than the hard igneous and metamorphic bedrock found in the east. Harder, denser rock generally transmits seismic waves better than softer, less dense rock, so earthquakes of given magnitude may be more severe over larger areas in the east than in the west. From the perspective of ground motion intensity, it is fortunate that more large earthquakes occur in the west than in the east.

Ground motions are measured as accelerations, the rate of change of motion. This type of force is the same as accelerating in a car, where the driver feels pushed gently back against the seat while increasing speed. This is a small force compared with another common force measured as an acceleration, gravity. Gravity is equal to 9.8 meters per second squared, or 1×g (this is what one would feel while jumping out of an airplane). People have trouble standing up and buildings begin falling at one-tenth the acceleration of gravity (0.1×g). Large earthquakes can produce accelerations that greatly exceed—even double or triple—the force of gravity. These accelerations are able to uproot large trees and toss them into the air, shoot objects through walls and buildings, and cause almost any structure to collapse.

Some of the damage typically associated with ground motion and the passage of seismic waves includes swaying and pancaking of buildings. During an earthquake buildings may sway with a characteristic frequency that depends on their height, size, construction, underlying material, and intensity of the earthquake. This causes heavy objects to move rapidly from side to side inside the buildings and can cause much destruction. The shaking generally increases with height, and in many cases the shaking causes concrete floors at high levels to separate from the walls and corner fastenings, causing the floors to fall progressively or, pancake one another, crushing all in between. With greater shaking the entire structure may collapse.

Ground Breaks

Ground breaks, or ruptures, form where a fault cuts the surface, and they may also be associated with mass wasting, or the movements of large blocks of land downhill. These ground breaks may have horizontal, vertical, or combined displacements across them and may cause considerable damage. Fissures that open in the ground during some earthquakes are mostly associated with the mass movement of material down slope, not with the fault trace itself breaking the surface. For instance, in the Alaskan earthquake (1964) ground breaks displaced railroad lines by several yards (m); broke through streets, houses, storefronts, and other structures; and caused parts of them to drop by several yards (m) relative to other parts of the structure. Most of these ground breaks were associated with slumping, or movement of the upper layers of the soil downhill toward the sea. Ground breaks during earthquakes are also one of the causes of the rupture of pipelines and communication cables.

Mass Wasting

Mass wasting is the movement of material downhill. In most instances mass wasting occurs by a gradual creeping of soils and rocks downhill, but during earthquakes large volumes of rock, soil, and all that is built on the area affected may suddenly collapse in a landslide. Earthquake-induced landslides occur in areas with steep slopes or cliffs, such as parts of California, Alaska, South America, Turkey, and China. One of the worst recorded earthquake-

A second photograph of damage from ground shaking and landslides in Hongkon, Sichuan Province, China, from May 12, 2008, magnitude 7.9 earthquake *(T. Kusky)*

Damage from ground shaking and liquefaction in Yingxin, Sichuan Province, China, causing buildings to collapse on their sides, from May 12, 2008, magnitude 7.9 earthquake *(T. Kusky)*

induced landslides occurred in the magnitude 7.9 Wenchuan, China, earthquake (2008) when several villages were completely buried under hundreds of feet of debris from mountains that collapsed nearby, killing thousands.

In the 9.2 magnitude Alaska earthquake (1964), landslides destroyed power plants, homes, roads, and railroad lines. Some landslides even occurred undersea and along the seashore. Large parts of Seward and Valdez sat on the top of large submarine escarpments, and during the earthquake extensive areas of these towns slid out to sea in giant submarine landslides and were submerged. Another residential area near Anchorage, Turnagain Heights, was built on top of cliffs with fantastic views of the Alaska Range and Aleutian volcanoes. When the earthquake struck, this area slid out toward the sea on a series of curving faults that connected in a slippery shale unit known as the Bootlegger shale. During the earthquake this shale unit lost all strength and became almost cohesionless, and the shaking of the soil and rock above it caused the entire neighborhood to slide toward the sea along the shale unit and be destroyed.

Liquefaction

Liquefaction is a process in which sudden shaking of certain types of water-saturated sands and muds turns these once-solid sediments into slurry with a liquidlike consistency. Liquefaction occurs where the shaking causes individual grains to move apart, then water moves up in between the individual grains, making the whole water/sediment mixture behave like a fluid. Earthquakes often cause liquefaction of sands and muds. Any structures built on sediments that liquefy may suddenly sink into them as if resting on a thick fluid. Liquefaction caused the Bootlegger shale in the 1964 Alaskan earthquake to become suddenly so weak that it destroyed Turnagain Heights. Liquefaction during earthquakes also causes sinking of sidewalks, telephone poles, building foundations, and other structures. One famous example of liquefaction occurred in the Japan earthquake (1964), where entire rows of apartment buildings rolled onto their sides but were not severely damaged internally. Liquefaction also causes sand to bubble to the surface during earthquakes, forming mounds up to several tens of feet high, known as sand volcanoes, or ridges of sand.

Changes in Ground Level

During earthquakes, blocks of earth shift relative to one another. This may result in changes in ground level, base level, the water table, and high-tide marks. Particularly large shifts have been recorded from some of the historically large earthquakes, such as the magnitude 9.2 Alaskan earthquake (1964) and the Sumatra earthquake (2004). In 1964 an area more than 600 miles (1,000 km) long in south central Alaska recorded significant changes in ground level, including uplifts of up to 12 yards (11 m), downdrops of more than two yards (2 m), and lateral shifts of several to tens of yards. Uplifted areas along the coastline experienced dramatic changes in the marine ecosystem—clam banks were suddenly uplifted out of the water and remained high and dry. Towns built around docks were suddenly located many yards above the convenience of being at the shoreline. Downdropped areas experienced different effects—forests that relied on freshwater for their root systems suddenly were inundated by salt water and were effectively "drowned." Populated areas located at previously safe distances from the high tide (and storm) line became prone to flooding and storm surges, and had to be relocated.

Areas far inland also suffered from changes in ground level—when some were uplifted by many tens of feet (~10 m), the water table recovered to a lower level relative to the land surface, and soon became out of reach of many water wells, which had to be redrilled. Changes in ground level, although seemingly a minor hazard associated with earthquakes, are significant and cause a large amount of damage that may cost millions of dollars to mitigate.

Tsunamis and Seiche Waves

Several types of large waves are associated with earthquakes, including tsunamis and seiche waves. Tsunamis, also known as seismic sea waves, form most usually from submarine landslides that displace a large volume of rock and sediment on the seafloor, which in turn displaces a large amount of water. Tsunamis may be particularly destructive as they travel very rapidly (hundreds of miles per hour), and may reach many tens of yards above normal high-tide levels. The most devastating tsunami in recorded history occurred in 2004, in association with the magnitude 9.0 earthquake in Sumatra, Indonesia. A wave that reached heights locally of 100 feet (30 m) swept across the Indian Ocean, killing about 283,000, mostly in Indonesia, Sri Lanka, and India. Two other particularly devastating examples include a tsunami generated by a magnitude 8.7 earthquake in the Atlantic Ocean (1775) that is estimated to have killed more than 60,000 in Portugal (this number is from Lisbon alone, although the tsunami struck a large section of coastline, and other related tsunamis were reported from North Africa, the British Isles, and the Netherlands). Another tsunami generated in the Aleutian Islands of Alaska (1946) traveled across the Pacific Ocean at 500 miles per hour (800 km/hr) and hit Hilo, Hawaii, with a crest 18 yards (16 m) higher than the normal high-tide mark, killing 159 people, destroying approximately 500 homes, and damaging 1,000 more structures.

Seiche waves may be generated by the back-and-forth motion associated with earthquakes, causing a body of water (usually lakes or bays) to rock back and forth, gaining amplitude and splashing up to higher levels than normally associated with that body of water. The effect is analogous to shaking a glass of water and watching the ripples suddenly turn into large waves that splash out of the glass. Other seiche waves may be formed when landslides or rockfalls drop large volumes of earth into bodies of water. The largest recorded seiche wave of this type formed suddenly on July 9, 1958, when a large earthquake-initiated rockfall generated a seiche wave 1,700 feet (518 m) tall. The seiche wave raced across Lituya Bay, Alaska, destroying the forest and killing several people, including a geologist who had warned authorities that such a wave could be generated by a large landslide in Lituya Bay.

Damage to Utilities (Fires, Broken Gas Mains, Transportation Network)

Much of the damage and many of the casualties caused by earthquakes are associated with damage to the infrastructure and system of public utilities. For example, much of the damage associated with the San Francisco earthquake (1906) came not from the earthquake itself but from the huge fire that resulted from the numerous broken gas lines, overturned wood and coal stoves, and even from fires set intentionally to collect insurance money on partially damaged buildings. In the Kobe, Japan, earthquake (1995), a large share of the damage was likewise from fires that raged uncontrolled, with fire and rescue teams unable to reach the areas worst affected. Water lines were broken so that even in accessible locations, firefighters were unable to put out the flames.

One of the lessons from these examples is that evacuation routes need to be set up in earthquake hazard zones in anticipation of post-earthquake hazards such as fires, aftershocks, and famine. These routes should ideally be clear of obstacles such as overpasses and buildings that may block access, and efforts should be made to clear these routes soon after earthquake disasters, both for evacuation purposes and for emergency access to the areas worst affected.

See also GEOLOGICAL HAZARDS; PLATE TECTONICS; SEISMOLOGY; TSUNAMI, GENERATION MECHANISMS.

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economic geology The science of economic geology focuses on the study of earth materials that can be used for economic or industrial purposes. Different subfields include the study of ore deposits and metals; nonmetallic resources such as hydrocarbons and petroleum; gems; and industrial materials for construction and for high-technology fields. Complete analysis of economic resources includes several disciplines of geology, including field geology, geophysics, geochemistry, and structural geology, but also extends to other fields such as investment banking, stock and futures markets analysis, and economic and government planning. The mining of economic resources also brings in environmental scientists and planners who must make sure that the development of economic resources is done with the least detrimental impact on the environment.

MINERAL RESOURCES AND OCCURRENCES AND ORE RESERVES

Geologic processes concentrate many minerals in the Earth's crust, and some of these have economic value of potential benefit to society. When a rare, potentially valuable mineral is concentrated in a location but in quantities too low to be of economic or minable value, it is said to be a mineral occurrence. When the concentration reaches a critical value that makes it minable in current or potentially future economic scenarios, it is classified as a mineral resource. Ore reserves are concentrations of minerals that are economically and technically feasible to extract.

Different types of mineral resources include metallic ores, nonmetallic ores, gems, hydrocarbons, and building materials. Descriptions of the metallic ore deposits are covered here, and links to the nonmetallic ores and resources are cited in the discussions listed at the end of this entry.

THE FORMATION AND CONCENTRATION OF METALLIC ORE DEPOSITS

Most metallic ores form by one of several main processes, including concentration by hydrothermal fluids, crystallization from an igneous magma, metamorphic processes that move fluids and chemical components in rocks from place to place, weathering, sorting by water in streams, or other surficial processes that can remove some elements from a rock or soil while concentrating other elements.

Many of the ores of metallic minerals occur as compounds of the sulfide ion, S^{2-}, with the metals attached as cations. Most of these are soft, resemble metals, and form many of the world's large ore deposits. One of the most common sulfide minerals is pyrite, FeS_2, found as a minor component in many rocks and as an accessory mineral in many ore deposits. Pyrrhotite (Fe_7S_8-FeS) is a less common iron sulfide mineral. Most ore deposits are formed from hydrothermal fluids. Lead (Pb) and Zinc (Zn) are commonly found in sulfide compounds such as galena (PbS) and sphalerite (ZnS), and copper deposits are dominated by the sulfide minerals chalcopyrite ($CuFeS_2$) and bornite (Cu_5FeS_4).

Iron Ore

Iron is one of the most important metalliferous ores used globally for construction, the automobile industry, and a number of other commodities. Most iron ore is found in Precambrian-banded iron formations (BIFs), such as in the Hamersley Basin of Australia, and include finely layered sequences of sedimentary rocks with thin layers of iron oxide minerals, typically interlayered with chert or other silica-rich layers. Most banded iron formations are Archean or Proterozoic in age, and many models suggest that they required special environmental conditions to form, including an oxygen-poor atmosphere, and a setting in which submarine volcanic eruptions were able to help transport the iron to seafloor settings where it was deposited. Many of these deposits were later weathered so that the magnetite in the original deposits was altered by oxidation to hematite, a form of iron more easily mined and used by the steel industry.

Lead-Zinc-Silver Ores

Many deposits of lead and zinc are associated with silver and are found in submarine settings that formed in association with volcanism, forming a type of deposit known as a SEDEX (sedimentary exhalative) deposit. These tend to be associated with the fringes of large volcanic flows or on the margins of subvolcanic plutons, with many examples located in the Superior craton of Canada and others in Australia. Another, quite different type of lead-zinc deposit is found as metalliferous layers that replaced primary carbonate layers; the world's largest deposit of this type is found in the central United States in Missouri, in the Mississippi valley lead-zinc deposit belt.

Gold

Gold is found in a diverse array of deposit types, ranging from concentrations in quartz veins in igneous-metamorphic rocks controlled by the plate tectonic setting, to metamorphic settings, to wide areas called alluvial deposits where streams eroded primary gold sources and deposited them in places where the stream currents slowed and dropped the gold out of suspension. Most of the lode gold deposits are found in quartz veins in intrusions, granites, shear zones, and deformed turbidite sequences. Basalt is a common constituent of many gold provinces, and it appears that metamorphic fluids move through the basalt and leach out the gold and related fluids, depositing them when the chemical and temperature conditions are best suited in the host rocks.

Placer gold is eroded from the lode gold sources and carried by streams and rivers, or reworked by beach processes before reaching the final site of deposition. Most of the the world's placer gold is found in the Archean Witwatersrand Basin in South Africa, but many other placer gold provinces are known from around the world. One of the most active of these, where the lode-gold sources were identified well after the placer layers, is the gold districts of Alaska.

Photo of gold-quartz vein *(Layne Kennedy/Corbis)*

Historical Note on the Placer Gold Deposits of Alaska

The placer gold deposits of Alaska and the Yukon Territories lured tens of thousands of frontiersmen to the wild and dangerous territories of the north in the late 1800s and early 1900s. Life was extremely tough, the rewards few, and dangers many, but some of these frontiersmen did find gold and managed to settle the north.

Gold typically occurs as a native metal and is found in lode deposits or placer deposits. Lode gold includes primary deposits in hard bedrock or in vein systems in the bedrock. In contrast, placer deposits are secondary, concentrated in stream gravels and soils. Gold is chemically unreactive so it persists through weathering and transportation and concentrates in soils and as heavy minerals in stream gravel deposits known as placers. Placer gold was the sought-after treasure in the great gold rushes of the Fairbanks gold district and the Yukon Territories of Canada, where many placer and lode deposits are still being discovered and mined.

The placer gold mining in Alaska was started after George Washington Carmack and his Native American brothers-in-law Skookum Jim and Tagish Charlie discovered rich deposits of placer gold on a tributary of the Klondike River in the Yukon Territory in 1896. Tens of thousands of would-be gold miners rushed to the Klondike in 1897–98, and many more struggled over the treacherous Chilkoot and White Passes in 1898, only to find that all of the streams and rivers in the area had already been claimed. Many of these enterpreneurs continued moving north into the wilderness of Alaska in their quest for gold. Alaska had been purchased from Russia only in 1867 and offered a new frontier for the United States. Gold had been reported from the Russian River on the Kenai Peninsula in 1834, and in 1886 the first major discovery of gold in interior Alaska was reported from the Fortymile River. Other gold deposits were known from Birch Creek, in what is now the Circle mining district.

The miners who left the Klondike district continued down the Yukon River to the coast on the Seward Peninsula and found gold on the beaches at Nome, starting a new gold rush to the coast. The beaches at Nome were also quickly staked and claimed, and many thousands of explorers and potential gold miners stopped between the Yukon and the Nome beaches, searching for the precious metal in the soils and gravels of central Alaska. In 1902 Italian gold prospector Felix Pedro found gold along a tributary to the Tanana River, at the site of what is now the city of Fairbanks. This became the next gold rush area in Alaska, and has led to many years of gold exploitation along the rivers, as well as the establishment of what has become one of Alaska's biggest cities, founded on the concentration of gold in the regolith.

The early placer mining techniques were very labor intensive, with minors digging gravel from the streams, moving it in wheelbarrows, and washing it in sluices and gold pans in search for the metal. Later, near the turn of the century, new techniques were developed in which miners would build fires to melt the permafrost, tunnel to 20 or 30 feet (6–10 m) into the gravel, and excavate huge piles that were later sluiced in the search for gold. Later techniques saw powerful fire hose–like hydraulic nozzles used to thaw and loosen large quantities of gravel for sluicing, then in the 1930s steam-powered shovels and bucketline dredges rapidly increased the pace of mining. Only in the 1980s did environmental concerns stop these mining methods, by which time the entire environment had been stripped bare, then the barren gravels laid back in the stream channel. Now exploration for gold in the soils and regolith must be done under strict guidelines of the U.S. Environmental Protection Agency.

Platinum Group Elements

Some rare metals known as platinum group elements (PGEs) form economic concentrations in some ultramafic igneous rocks and take several forms. Chromite may occur as layers, typically in continental intrusions or as small pods in ultramafic rock associations. Chromite and platinum group elements are typically associated with sulfide minerals and form when there is enough sulfur in the magma to crystallize these phases while the rock is still in liquid forms. In many cases the metal phases are a result of contamination of the magma by melted country rock, particularly in the continental layered intrusions. Examples of large economic deposits of chromite are found in the Bushveld Complex in South Africa, and the Muskox and Stillwater Complexes of North America.

Nickel

Nickel deposits are typically found as concentrations in lateritic soils or in association with sulfide minerals in ultramafic magmatic rocks. Nickel occurs often with platinum group elements and has geochemical affinities that make it occur with sulfide minerals such as pyrite, chalcopyrite, and pyrrhotite in ultamafic rocks such as komatiites.

Other nickel deposits are found in tropical regions, where lateritic weathering leaches away many elements, leaving just the residual material such as nickel that is not soluble. These deposits, called nickel laterite deposits, are found in parts of Africa including Madagascar and in the Caribbean. In most cases the host rock is ultramafic, but in some examples the tropical weathering is so intense that the nickel and associated metals are concentrated from other host rocks. Gold may also be concentrated in some lateritic weathering profiles.

Copper Deposits

Most economic copper deposits are found in association with volcanic-plutonic arc sequences in porphyry copper deposits, but other economic resources of copper are known from sedimentary deposits. In porphyry copper deposits the copper is carried by the sulfide mineral chalcopyrite, which is enriched and carried upward by the granitic magmas and by hydrothermal fluids associated with the plutons. Copper is also often found in association with nickel, gold, lead, and zinc deposits. Copper can also form in deep oceanic settings, when brine fluids from deeply buried sediments discharge and deposit copper, lead, and zinc directly on the seafloor.

Uranium

Uranium ores generally come from granitic sources, where radioactive minerals such as monazites are leached from the granites, carried by acidic solutions, then deposited where the fluids meet neutralizing conditions such as are found in carbon-bearing sediments and, in some cases, along unconformity surfaces. Other uranium ores are found directly in the granitic host rock, such as Australia's Olympic Dam deposit, containing nearly 35 percent of the world's known sources of economically recoverable uranium.

See also ARCHEAN; BLACK SMOKER CHIMNEYS; FLYSCH; GEOCHEMISTRY; GRANITE, GRANITE BATHOLITH; GREENSTONE BELTS; HYDROCARBONS AND FOSSIL FUELS; IGNEOUS ROCKS; METASOMATIC; MINERAL, MINERALOGY; OPHIOLITES; PETROLEUM GEOLOGY; PLATE TECTONICS; PRECAMBRIAN; SOILS.

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ecosystem An ecosystem is an ecological unit that encompasses the total aspect of the physical and biological environment of an area and the connections between the various parts. It is an integrated unit consisting of a community of living organisms, affected by various factors such as temperature, humidity, light, soil, food supply, and interactions with other organisms, as well as the nonliving environments, including matter and energy. Changes in any part of an ecosystem are likely to result in changes in the other parts. Relationships between organisms in an ecosystem depend on changes in the energy input and flow and nutrient flux within the system. The term was coined in 1935 by British ecologist Arthur Tansley (1871–1955).

One of the principal ideas of the ecosystem concept is that living organisms interact in complex ways with their local environments, and change in one part of the system can cause changes in another. There is an overall flow of energy in ecosystems that includes exchange of material between living and nonliving parts of the system. In this way all species are ecologically related to each other, as well as with the abiotic constituents of the environment. Ecosystems are similar to biomes, which are climatically and biologically defined areas with a distinctive community of plants, animals, and soil organisms.

CLASSIFICATION OF ECOSYSTEMS

Ecosystems are classified based on ecological criteria as well as general climate and features recognizable from the field and from satellite imagery. Some are based on the seasonality of changes in the systems, such as changes in leaf characteristics, linked together with information on climate, elevation, humidity, and drainage. These criteria have been modified and adopted by 175 countries in the Convention on Biologic Diversity in Rio de Janeiro in June 1972. This convention had three main goals:

- conservation of biodiversity
- sustainable use of its components
- fair and equitable sharing of benefits arising from genetic resources.

Participants in this conference adopted a new, more encompassing definition of ecosystems as a "dynamic complex of plant, animal, and microorganism communities and their nonliving environment interacting as a functional unit."

Following the criteria and goals of the conference, several different ecological classification systems became widely used. The first is physiognomic-ecological classification of plant formations of the Earth, differentiating between the structures and appearance from above ground and underwater plant systems. The second is a land cover classification system (LCSS) developed by the Food and Agriculture Organization, based mainly on satellite-based observations.

An outcome of the increased attention on ecosystems is the definition of ecosystem services, which are fundamental life-support services on which civilization depends. Such services include pollination, flood control, food for cattle in natural grasslands, wood for the timber industry, erosion, nutrient cycling, natural products for the pharmaceutical industry, and bush meat for indigineous populations. More effort has been made in recent years to assign economic value to ecosystem services, which helps preserve these ecosystems by increasing society's awareness of their inherent value. Secondary services derived from natural ecosystems include natural reserves for populations to enjoy nature, water storage and controls, soil protection, and carbon sequestration. All of these can be assigned commercial values and treated as commodities that can be bartered against pressures to develop threatened ecosystems commercially.

Some of the less concrete values of preserving ecosystems come from the preservation of biodiversity, where preserving the natural environment may help individual organisms in the ecosystem be more resilient to change and avoid extinction, and may eventually contribute to the benefit of humans, for instance, by the discovery of new medicines or ecosystems critical to the stability of the planet's climate.

ECOSYSTEM DYNAMICS

Ecosystems work through the exchange of energy and matter between the various biologic and nonbiologic components of the system. Introduction of new components, or the loss of any component, typically disrupts the system, and some changes can be so severe that they cause a cascading effect and the collapse of the entire ecosystem. In other cases the ecosystem can recover from the introduction of a new toxin, predatory species, or other disruptive agent. The ability of the ecosystem to recover depends on the toxicity of the new element and the resiliency of the original ecosystem.

See also BIOSPHERE; CARBON CYCLE; GAIA HYPOTHESIS; GEOCHEMICAL CYCLES.

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Einstein, Albert (1879–1959) German, Swiss *Theoretical Physicist* Albert Einstein was one of the most influential physicists of modern times. He is best known for his theory of relativity and for deriving the equivalence between mass and energy expressed as the following:

$$E = mc^2$$

where E equals energy, m is mass, and c is the speed of light. Einstein won the Nobel Prize in physics in 1921 "for his services to theoretical physics, and especially for his discovery of the photoelectric effect." His most significant contributions include his special theory of relativity, which reconciles mechanics and electromagnetism, and the general theory of relativity, which deals with gravitation and applying the ideas of relativity to nonuniform motion. He also pioneered many contributions in cosmology, mechanics, quantum theory, light and radiation, and unified field theory. Albert Einstein authored more than 300 scientific papers and 150 other works.

EARLY LIFE AND FAMILY

Albert Einstein was born on March 14, 1879, to Hermann Einstein and Pauline (Koch) Einstein, a Jewish family in the kingdom of Württemberg in the German Empire. His father was an engineer and salesman, and the family moved to Munich in 1880, where his father and uncle founded an electrical manufacturing company.

One of the defining moments of Albert's childhood was at age five when his father showed him a compass and the young Einstein realized that there must be something in space that caused the compass needle to move, a realization that proved to be a source of inspiration to him in his early years. Albert developed a hobby of building models and mechanical devices and he developed a talent for mathematics at a young age.

When Albert was 10, a medical student, Max Talmud, introduced Albert to textbooks on classical science, mathematics, and philosophy, including Euclid's *Elements* (referred to by Albert as the "holy little geometry book"), which he mastered by age 12 and moved on to infinitesimal calculus. In his early teens, Einstein grew bored with the regimen of the electrical engineering program his father was encouraging him to pursue at the Luitpold Gymnasium School, and he sought more creative learning. In 1894 his father's business failed and the family moved to Milan, Italy, then on to Pavia. During this time, at the age of 15, Einstein wrote his first scientific paper, which he sent to his uncle Casar Koch, entitled "The Investigation of the State of Aether in Magnetic Fields." Einstein's family left him in Munich to complete his schooling, but missing them, he withdrew from school and traveled to Pavia to rejoin them.

Albert Einstein never finished high school in Munich after that event. He tried to get accepted at the Swiss Federal Institute of Technology (ETH) in Zurich, but failed the entrance exam. His family arranged for him to finish school in Aarau, Switzerland, while boarding with Professor Jost Winteler. While living with the Winteler family Einsten fell in love with their daughter Marie and courted her from 1895 to 1901. He finished his schooling at age 17, renounced his German citizenship to avoid military service, and moved to Zurich, where he finally enrolled in the mathematics program at ETH. There he met his future wife, Serbian Mileva Marič, who was enrolled at ETH as the only woman studying mathematics. Einstein graduated in 1900 with a degree in physics, wrote a prestigious paper first clearly explaining capillary forces, and received Swiss citizenship in 1901.

Einstein married Mileva Marič in 1903, after she gave birth to a mentally handicapped daughter in 1902. The fate of their daughter is unknown, and it is likely that she died of scarlet fever in 1903 or was adopted and raised by a friend of the Marič family, Helene Savič. They also had two sons, Hans Albert, born in Bern, Switzerland, on May 14, 1904, and Eduard, born in Munich, Germany, on July 28, 1910. Einstein and Marič lived apart for five years and divorced on February 14, 1919. On June 2, 1919, he remarried, this time to his cousin Elsa, and though they raised Elsa's daughters from a previous marriage, they had no children together.

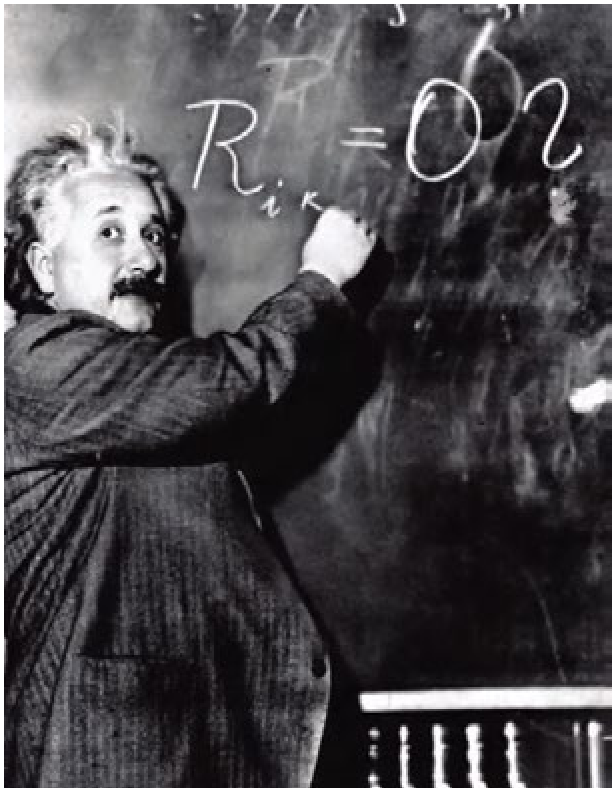
EARLY CAREER

After Einstein graduated from ETH he could not find a university teaching position, so he took a job in 1902 at the patent office in Bern, where he evaluated patent applications for electromagnetic devices. During this time he formed a discussion group in which he met with friends to discuss science and philosophy. Einstein's job in the patent office may have influenced his later thinking, since many of the patents he handled had to do with the synchronization of electrical and mechanical signals. This experience helped him establish many of the questions about the fundamental nature of light and connections between space and time.

While he was working in the patent office he published four papers in *Annalen der Physik*, the top German physics journal at the time. These papers have become known as the annus mirabilis (extraordinary year) papers because of their far-reaching implications and importance. His first paper in this group was on the particulate nature of light and how the photoelectric effect could be understood as light behaving as discrete quanta of energy. His next annus mirabilis paper was on Brownian motion, explaining the random movement of small objects as being caused by molecular action, supporting the atomic theory. Einstein's third paper in this series was on special relativity, where he showed that the speed of light was independent of the observer's speed or state of motion. His final annus mirabilis paper was perhaps his most famous; in it he derived the equivalence of mass and energy as described by the equation

$$E = mc^2$$

showing that mass could be converted into energy and predicting the future development of nuclear power. Although modern science recognizes these papers as remarkable achievements and some of the most important works in physics of all time, the physics community barely noticed them, and many actually rejected them as nonsense. At the age of 26 Einstein earned a Ph.D. from ETH under the direction of Alfred Kleiner, after submitting his dissertation, "A New Determination of Molecular Dimensions."



Albert Einstein, shown writing an equation for the density of the Milky Way Galaxy at Carnegie Institution, Mount Wilson Observatory headquarters, Pasadena, California, on January 14, 1931 *(AP Images)*

LATER SCIENTIFIC CONTRIBUTIONS

In 1908 Einstein finally received an academic position at the University of Bern, which gave him the title privatdozent (roughly equivalent to a postdoctoral researcher, granted by some European universities for those who hold a Ph.D. and Habilitation and want to pursue an academic career). Einstein published a paper in 1910 on critical opalescence, describing how light is scattered by molecules in the atmosphere, making the sky appear blue. He also worked more on the quantization of light, showing that light and energy quanta must act as independent pointlike particles. He published this in two papers, including one entitled "The Development of Our Views on the Composition and Essence of Radiation." This work led to the idea of the wave-particle dual nature of light in quantum mechanics.

Einstein took a position as associate professor at the University of Zurich in 1911, then moved quickly to a full professorship at the Charles University of Prague, in the present-day Czech Republic. From there he published a new paper on the effects of gravity on light and the gravitation redshift of light, including a test of the model later confirmed during a solar eclipse.

In 1912 Einstein returned as a full professor at ETH, where he worked on gravitational theory, eventually publishing his general theory of relativity in 1915. The basic idea of general relativity is that gravitation is the distortion of space-time by matter, which affects the inertial motion of other matter.

World War I broke out in 1914 and Marič moved to Zurich while Einstein moved to Berlin, where he became a member of the Prussian Academy of Sciences and professor at the Humboldt University of Berlin, and served as director to the Kaiser Wilhelm Institute for Physics from 1914 to 1932. He also accepted a position as an extraordinary professor at Leiden University, and he traveled to Holland regularly to lecture between 1920 and 1930.

In 1917 Einstein published a paper that added the cosmological constant to his theory of general relativity, in an attempt to explain the behavior of the entire universe. Einstein later abandoned this constant, although new observations in the 1990s suggest that he may have been correct. In 1917 different groups of astronomers also began testing Einstein's prediction of the gravitational redshift of light, but all groups claimed to have disproved his theories until 1919, when the team of British astronomer Arthur Eddington confirmed the gravitational deflection of starlight by the Sun during an eclipse, proving Einstein correct. Scientists around the world then recognized the importance of Einstein's work, with British Nobel laureate Paul Dirac claiming Einstein's theory was "the greatest scientific discovery ever made."

Albert Einstein was awarded the 1921 Nobel Prize in physics "for his service to theoretical physics, and especially for his discovery of the law of the photoelectric effect." The prize was awarded specifically for his paper on the photoelectric effect entitled "On a Heuristic Viewpoint Concerning the Production and Transformation of Light." His theory of relatively was also mentioned but said to be controversial. Earlier that year, while in New York, Einstein was quoted as saying that scientific work proceeds best by examining physical reality and searching for underlying axioms that give consistent explanations that apply in all instances and that do not contradict one another.

After receiving the Nobel Prize and his work on general relativity, Einstein focused on unifying the fundamental laws of physics (including those governing electromagnetism and gravity) into a unified field theory. He was never successful at this (nor was anyone else to date), and as time passed he became progressively more isolated in the physics community, arguing publicly with Danish physicist and Nobel laureate Niels Bohr about scientific determinism and whether or not quantum phenomena are inherently probabilistic or not, and even ignoring many major developments such as the discoveries of the strong and weak nuclear forces. Einstein's drive to find a unifying field theory survives in physics as the current search for a grand unifying theory.

In 1933 Adolf Hitler became chancellor of Germany and immediately removed Jews and other politically suspect employees from office, including from university professorships. Einstein had been active in discussions of science and religion and in the proposed establishment of the State of Israel, and was prudent enough to have left Germany in 1932 and taken up residence in the United States. He spent time at the California Institute of Technology in Pasadena, and at the Institute for Advanced Study in Princeton, New Jersey. After his wife, Elsa, died in 1936, he continued at the Institute for Advanced Study and also became active in helping obtain visas for European Jews trying to flee Nazi persecution and genocide, helping to form the International Rescue Committee.

Meanwhile, in Germany, a campaign by German physicists including Philipp Lenard and Johannes Stark was mounted to try to discredit Einstein's work as "Jewish physics," and there were attempts made to claim his work was done instead by Aryan physicists. Einstein was granted U.S. citizenship, then teamed up with the Hungarian Jewish refugee and physicist Leo Szilard to persuade U.S. President Franklin Roosevelt to develop an atomic weapon before the Germans did, and by 1942 this effort developed into the Manhattan Project. By 1945 the United States had developed operational nuclear weapons and used them on the Japanese cities of Hiroshima and Nagasaki in August 1945, killing 220,000 people and leading to the end of World War II. Einstein made public statements that he did not work on the atomic bomb projects, and that he regretted writing the letter to Roosevelt asking that such research be started.

Einstein was taken to Princeton Hospital on April 17, 1955, for internal bleeding caused by a ruptured aortic aneurysm. He brought along a speech he was working on to commemorate the seventh anniversary of the founding of Israel, but he died the next morning at the age of 76. Before Einstein was cremated the hospital pathologist, without permission, removed Einstein's brain, which has been preserved for science, but the doctor who removed the organ was fired for performing the act without permission of the family. His brain was sliced up and pieces given to various researchers, including Dr. Marian Diamond from the University of California, Berkeley. Other pieces were sent to researchers at Princeton University, and McMaster University in Hamilton, Ontario, Canada.

See also ASTRONOMY; ASTROPHYSICS; COSMOLOGY; GENERAL RELATIVITY; GRAVITY, GRAVITY ANOMALY; ORIGIN AND EVOLUTION OF THE UNIVERSE.

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electromagnetic spectrum

The electromagnetic spectrum refers to the total range of all possible electromagnetic radiation frequencies, ranging from the smallest gamma rays with wavelengths a fraction the size of an atom, through X-rays, ultraviolet rays, visible radiation, infrared rays, microwave, and radio waves. The spectrum of an object refers to the characteristic distribution of radiation that comes from that object. The wavelengths of the radiation range from gamma rays at 10^{-14} meters, a fraction of an atom, to 10^{4} meters, or radio waves that can be thousands of km long. The electromagnetic spectrum is open-ended, so in theory the largest wavelengths of radiation approach the size of the universe, and the smallest are the size of a proton (6.3×10^{-34} inches, or 1.6×10^{-35} m).

Electromagnetic energy is characterized by a specific wavelength λ, at which it has an associated frequency f and photon energy E. The electromagnetic spectrum is therefore expressed by the following three equations:

$$\lambda = c/f$$
$$E = hc/\lambda$$
$$E = hf$$

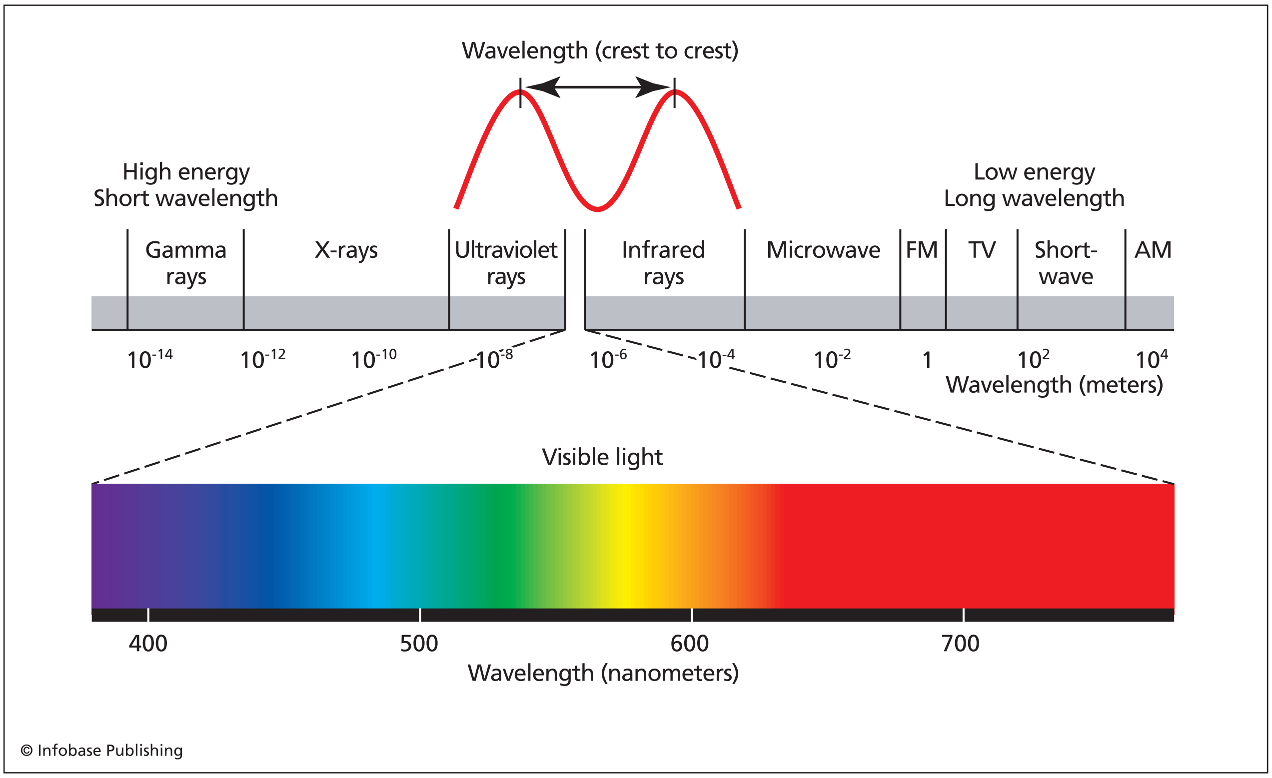
where c = the speed of light (299,792,458 m/sec), and h = Planck's constant, $6.626068\ 96 \times 10^{-34}$ J·s. These equations mean that high-frequency electromagnetic waves have a short wavelength and high energy, whereas low-frequency waves have a long wavelength and low energy.

The wavelength of electromagnetic radiation is expressed using its wavelength in a vacuum. When the radiation travels though any medium, such as air or water, its wavelength is always decreased. This is important since the behavior of electromagnetic radiation depends on its wavelength. Higher-frequency radiation has shorter wavelengths, and lower-frequency radiation has longer wavelengths. Electromagnetic radiation is also associated with a specific amount of energy, and has a dual nature, as both a wave and a particle, as described by quantum mechanics. When electromagnetic radiation interacts with small particles such as molecules and single atoms, the quantum effects become important, and the behavior of the radiation is then best described as the amount of energy that each quantum contains. In terms of energy levels electromagnetic radiation is divided into octaves, much as sound waves are divided this way. The table "Characteristics of Electromagnetic Radiation" compares the different wave and particle energy levels of the electromagnetic spectrum.

TYPES OF ELECTROMAGNETIC RADIATION

The electromagnetic spectrum is usually divided into several different regions according to wavelength, with the most common classification scheme including radio waves, microwaves, terahertz radiation, infrared radiation, visible light, ultraviolet light, X-rays, and gamma rays.

Radio waves have wavelengths from one millimeter to hundreds of meters and frequencies of about 3 Hz to 300 GHz. They are commonly used to transmit data for television, mobile phones, wireless Internet connections, and many other applications.



The electromagnetic spectrum

The complex technology to encode radio waves with data involves changing the amplitude and frequency and phase relations of waves within a specific frequency band.

Microwave radiation wavelengths range from one millimeter to one meter and frequencies between 0.3 GHz and 300 GHz. It includes super-high-frequency (SHF) and extremely-high-frequency classes. Microwaves are absorbed by molecules with dipolar covalent bonds, a property used to heat material uniformly, and in rapid amounts of time, in microwave ovens.

Terahertz radiation wavelengths range between the far infrared and microwaves, and frequencies between 300 GHz and 3 terahertz. Radiation in this region can be used for imaging and communications and in electronic warfare to disable electronic equipment.

Infrared radiation has wavelengths between visible light and terahertz radiation, and frequencies of 300 GHz (1 mm) to 400 Terra Hertz (750 nm). Far-infrared radiation (300 GHz to 30 THz) is absorbed by the rotation of many gas molecules, by the molecular motions in liquids, and by phonons (a quantized mode of vibration of a crystal lattice) in solid phases. Most of the far-infrared radiation that enters the Earth's atmosphere is absorbed except for a few wavelength ranges (called windows) where some energy can penetrate. Mid-infrared radiation has frequencies from 30 to 120 THz, and includes thermal radiation from black bodies (i.e., bodies that absorb all energy at all wavelengths when they are cold). Near-infrared radiation is similar to visible light and has frequencies from 120 to 400 THz.

Higher-frequency radiation (400–790 THz) with wavelengths between 400 and 700 nanometers is detectable by the human eye and is known as visible light. It is also the range of most of the radiation emitted from the Sun and stars. When objects reflect or emit light in the visible range, the human eye and brain process data from these wavelengths into an optical image of the object. The details of how the human brain perceives radiation from these wavelengths and processes it into an image is not completely understood and is actively studied by many molecular biologists, neuroscientists, psychologists, and biophysicists.

Ultraviolet radiation has wavelengths shorter than visible light and longer than X-rays, falling between 400 and 10 nm, and has energies between 3 and 124 electron volts. Ultraviolet radiation is emitted by the Sun and is a highly energetic ionizing radiation that can induce chemical reactions, may cause some substances to glow or fluoresce, and can cause sunburn on human skin. The ultraviolet radiation from the Sun is poisonous to most living organisms but is

CHARACTERISTICS OF ELECTROMAGNETIC RADIATION

Class	Frequency	Wavelength	Energy
Gamma rays	300 EHz	1 pm	1.24 MeV
Hard X-rays	30 EHz 3 EHz	10 pm 100 pm	124 keV 12.4 keV
Soft X-rays	300 PHz 30 PHz	1 nm 10 nm	1.24 keV 124 eV
Extreme ultraviolet	3 PHz	100 nm	12.4 eV
Near ultraviolet	300 THz	1 μm	1.24 eV
Near Infrared	30 THz	10 μm	124 meV
Mid-Infrared	3 THz	100 μm	12.4 meV
Far Infrared	300 GHz	1 mm	1.24 meV
Extremely high frequency	30 GHz	10 mm (1 cm)	124 μeV
Super high frequency	3 GHz	100 mm (1 dm)	12.4 μeV
Ultra high frequency	300 MHz	1 m	1.24 μeV
Very high frequency	30 MHz	10 m	124 neV
High frequency	3 MHz	100 m	12.4 neV
Medium frequency	300 kHz	1 km	1.24 neV
Low frequency	30 kHz	10 km	124 peV
Very low frequency	3 kHz	100 km	12.4 peV
Voice frequency	300 Hz	1 Mm	1.24 peV
Super low frequency	30 Hz	10 Mm	124 feV
Extremely low frequency	3 Hz	100 Mm	12.4 feV

absorbed by the atmospheric ozone layer, preventing significant damage to life on Earth.

X-rays have wavelengths from 10 to 0.01 nanometers with frequencies from 30 petahertz to 30 exahertz (30×10^{15} Hz to 30×10^{18} Hz) and energies from 120 eV to 120 keV. X-rays can "see" through some objects (like flesh) but not others (like bones) and can be used to produce images for diagnostic radiography and crystallography. In the cosmos X-rays are emitted by neutron stars, some nebulae, and the accretion disks around black holes.

Gamma rays are the most energetic photons and have no lower limit to their wavelength. Their frequency is greater than 10^{19} Hz, their energies are more than 100 keV, and their wavelengths are fewer than 10 picometers. Gamma rays are highly energetic and ionizing, so they can cause serious damage to human tissue and are a serious health hazard.

See also ASTRONOMY; ASTROPHYSICS; CORIOLIS EFFECT; COSMIC MICROWAVE BACKGROUND RADIATION; INTERSTELLAR MEDIUM; ORIGIN AND EVOLUTION OF THE UNIVERSE; REMOTE SENSING.

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El Niño and the Southern Oscillation (ENSO) El Niño-Southern Oscillation is the name given to one of the better-known variations in global atmospheric circulation patterns. Global oceanic and atmospheric circulation patterns undergo frequent shifts that affect large parts of the globe, particularly those arid and semiarid parts affected by Hadley Cell circulation. Fluctuations in global circulation can account for natural disasters, including the dust bowl days of the 1930s in the midwestern United States. Similar global climate fluctuations may explain the drought, famine, and desertification of parts of the Sahel, and the great famines of Ethiopia and Sudan in the 1970s and 1980s.

The secondary air circulation phenomenon, the El Niño-Southern Oscillation, can also profoundly influence the development of drought conditions and desertification of stressed lands. Hadley cells migrate north and south with summer and winter, shifting the locations of the most intense heating. Several zonal oceanic-atmospheric feedback systems influence global climate, but the most influential is that of the Austral-Asian system. The location of the most intense heating in Austral-Asia in normal Northern Hemisphere summers shifts from equatorial regions to the Indian subcontinent along with the start of the Indian monsoon. Air is drawn onto the subcontinent, where it rises and moves outward to Africa and the central Pacific. In Northern Hemisphere winters the location of this intense heating shifts to Indonesia and Australia, where an intense low-pressure system develops over this mainly maritime region. Air is sucked in, moves upward, and flows back out at tropospheric levels to the east Pacific. High pressure develops off the coast of Peru in both situations, because cold, upwelling water off the coast here causes the air to cool, inducing atmospheric downwelling. The pressure gradient setup causes easterly trade winds to blow from the coast of Peru across the Pacific to the region of heating, causing warm water to pile up in the Coral Sea, off the northeast coast of Australia. This also causes sea level to be slightly depressed off the coast of Peru, and more cold water upwells from below to replace the lost water. This positive feedback mechanism is rather stable—it enhances the global circulation, as more cold water upwelling off Peru induces more atmospheric downwelling, and more warm water piling up in Indonesia and off the coast of Australia causes atmospheric upwelling in this region.

This stable, linked atmospheric and oceanic circulation breaks down and becomes unstable every two to seven years, probably from some inherent chaotic behavior in the system. At these times the Indonesian-Australian heating center migrates eastward, and the buildup of warm water in the western Pacific is no longer held back by winds blowing westward across the Pacific. This causes the elevated warm water mass to collapse and move eastward across the Pacific, where it typically appears off the coast of Peru by the end of December. The ENSO events occur when this warming is particularly strong, with temperatures increasing by 40–43°F (22–24°C) and remaining high for several months. This phenomenon is also associated with a reversal of the atmospheric circulation around the Pacific such that the dry downwelling air is located over Australia and Indonesia, and the warm upwelling air is located over the eastern Pacific and western South America.

The arrival of El Niño is not good news in Peru, since it causes the normally cold upwelling and nutrient-rich water to sink to great depths, and the fish either must migrate to better feeding locations or die. The fishing industry collapses at these times, as does the fertilizer industry that relies on the bird guano normally produced by birds that eat fish and anchovies, which also die during El Niño events. The normally cold dry air is replaced with warm moist air, and the normally dry or desert regions of coastal Peru receive torrential rains with associated floods, landslides, death, and destruction. Shoreline erosion is accelerated in El Niño events, because the warm water mass that moved in from across the Pacific raises sea levels by 4–25 inches (10–60 cm), enough to cause significant damage.

The end of ENSO events also leads to abnormal conditions, in that they seem to turn on the "normal" type of circulation in a much stronger way than is normal. The cold upwelling water returns off Peru with such ferocity that it may move northward, flooding a 1–2° band around the equator in the central Pacific Ocean with water that is as cold as 68°F (20°C). This phenomenon is known as La Niña ("the girl," in Spanish).

The alternation between ENSO, La Niña, and normal ocean-atmospheric circulation has profound effects on global climate and the migration of different climate belts on yearly to decadal timescales and is thought to account for about a third of all the variability in global rainfall. ENSO events may cause flooding in the western Andes and southern California, and a lack of rainfall in other parts of South America, including Venezuela, northeastern Brazil, and southern Peru. It may change the climate, causing droughts in Africa, Indonesia, India, and Australia, and is thought to have caused the failure of the Indian monsoon in 1899, which spread regional famine with the deaths of millions. Recently the seven-year cycle of floods on the Nile has been linked to ENSO events, and famine and desertification in the Sahel, Ethiopia, and Sudan can be attributed to these changes in global circulation as well.

See also ATMOSPHERE; CLIMATE, CLIMATE CHANGE.

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energy in the Earth systems *Earth systems* is a term describing all of the interrelated systems on the planet Earth, including those in the geosphere, hydrosphere, biosphere, and atmosphere. Earth systems are driven by energy from internal and external sources. The main external source of energy is the Sun. Internal energy comes from two main sources: the decay of radioactive isotopes and gravitational energy from when the Earth was just forming about 4.5 billion years ago. The outward transfer of heat from these sources inside the Earth is measured as heat flow, and it powers the convection in the Earth's mantle, which in turn drives the motion of the tectonic plates on the planet's surface. Plate tectonics is associated with many of the major Earth surface processes, including volcanic eruptions, earthquakes, and the uplift and erosion of mountain systems. Energy from the Sun heats the Earth's surface and atmosphere and drives the convection in the atmosphere and oceans, producing winds, currents, and storms. Energy transfer from the Sun controls the climate in processes near the Earth's surface, where processes related to internal energy transfer come to the surface. This dynamic transfer of energy in the external energy system includes interaction with the results of internal processes. Cloud formation is influenced by uplifted mountain ranges, their motion is affected by rotation of the Earth, and the energy transfer on the surface of the Earth is dominated by the interaction of systems driven by external energy sources, with such physical features as mountain and volcanic eruptions powered by internal energy sources.

Geological and biological processes on Earth are driven by energy that ultimately comes from either inside the Earth or the Sun. These are intrinsic (or internal) and extrinsic (or external) sources of energy, respectively. Most geological processes, including plate tectonics, the activity of earthquakes, volcanoes, and uplift of mountain ranges, can be attributed to processes associated with the loss of heat from deep in the planet's interior. These intrinsic processes often work together with and interact with extrinsically driven processes, such as rain and water-flow systems that tend to erode the mountains that were uplifted by intrinsic processes.

INTERNAL ENERGY SOURCES: HEAT TRANSFER AND FLOW FROM DEEP IN THE EARTH

In geology crustal heat flow is a measure of the amount of heat energy leaving the Earth from internal energy sources, measured in calories per square centimeter per second. Typical heat-flow values are about 1.5 microcalories per centimeter squared per second, commonly stated as 1.5 heat flow units. Most crustal heat flow is due to heat production in the crust by radioactive decay of uranium, thorium, and potassium. Heat flow shows a linear relationship with heat production in granitic rocks. Some crustal heat flow, however, comes from deeper in the Earth, beneath the crust.

The Earth exhibits a huge variation in temperature, from several thousand degrees in the core to essentially zero degrees Celsius at the surface. The Earth's heat and internal energy were acquired by several mechanisms, including these:

- heat from accretion as potential energy of falling meteorites was converted to heat energy
- heat released during core formation, with gravitational potential energy converted to heat as heavy metallic iron and other elements segregated and sank to form the core soon after accretion
- heat production by decay of radioactive elements
- and heat added by late-impacting meteorites and asteroids, some of which were extremely large in early Earth history

Heat produced by these various mechanisms gradually flows to the surface by conduction, convection, or advection, and accounts for the component of crustal heat flow that comes from deeper than the crust.

Heat flow by conduction involves internal thermal energy flowing from warm to cooler regions, with the heat flux being proportional to the temperature difference, and a proportionality constant k, known as thermal conductivity, related to the material properties. The thermal conductivity of most rocks is low, about one-hundredth that of copper wire.

Advection involves the transfer of heat by the motion of material, such as transport or heat in a magma, in hot water through fractures or pore spaces, and, more important, on a global scale, by the large-scale rising of heated, relatively low-density buoyant material and the complementary sinking of cooled, relatively high-density material in the mantle. The large-scale motion of the mantle, with hot material rising in some places and colder material sinking in other places, is known as convection, an advective heat-transfer mechanism. For convection to occur in the mantle, the buoyancy forces of the heated material must be strong enough to overcome the rock's resistance to flow, known as viscosity. Additionally, the buoyancy forces must overcome the tendency of the rock to lose heat by conduction, since this would cool the rock and decrease its buoyancy. The balance between all of these forces is measured by a quantity called the Raleigh number. Convection in Earth materials occurs above a critical value of the Raleigh number, but below this critical value heat transfer is by conductive processes. Well-developed convection cells in the mantle are very efficient at transporting heat from depth to surface and are the main driving force for plate tectonics.

Heat transfer in the mantle is dominated by convection (advective heat transfer), except in the lower mantle near the boundary with the inner core (the D″ region), along the top of the mantle, and in the crust (in the lithosphere), where conductive and hydrothermal (also advective) processes dominate. The zones where conduction dominates the heat transfer are known as conductive boundary layers, and the lithosphere may be thought of as a convecting, conductively cooling boundary layer.

The main heat-transfer mechanism that takes internal energy from deep in the Earth's mantle to the near-surface region is convection. It is a thermally driven process where heating at depth causes material to expand and become less dense, causing it to rise while being replaced by complementary cool material that sinks. This moves heat from depth to surface in an efficient cycle since the material that rises gives off heat as it rises and cools, and the material that sinks gets heated only to rise again eventually. Convection is the most important mechanism by which the Earth releases heat, with other mechanisms including conduction, radiation, and advection. However, many of these mechanisms work together in the plate tectonic cycle. Mantle convection brings heat from deep in the mantle to the surface, where the heat released forms magmas that generate the oceanic crust. The midocean ridge axis is the site of active hydrothermal circulation and heat loss, forming black smoker chimneys and other vents. As the crust and lithosphere move away from the midocean ridges, they cool by conduction, gradually subsiding (according the square root of their age) from about 1.5–2.5 miles (2.5–4.0 km) below sea level. Heat loss by mantle convection is therefore the main driving mechanism of plate tectonics, and the moving plates can be thought of as the conductively cooling boundary layer for large-scale mantle convection systems.

The heat transferred to the surface by convection is produced by decay of radioactive heat-producing isotopes such as uranium 235, Thorium 232, and Potassium 40, remnant heat from early heat-producing isotopes such as I 129, remnant heat from accretion of the Earth, heat released during core formation, and heat released during impacts of meteorites and asteroids. During the early history of the planet at least part of the mantle was molten, and the Earth has been cooling by convection ever since. Estimating how much the mantle has cooled with time is difficult, but reasonable estimates suggest that the mantle may have been up to a couple of hundred degrees hotter in the earliest Archean.

The rate of mantle convection is dependent on the ability of the material to flow. The resistance to flow is a quantity measured as viscosity, defined as the ratio of shear stress to strain rate. Fluids with high viscosity are more resistant to flow than materials with low viscosity. The present viscosity of the mantle is estimated to be 10^{20}–10^{21} Pascal seconds (Pa/s) in the upper mantle and 10^{21}–10^{23} Pa/s in the lower mantle, viscosities sufficient to allow the mantle to convect and complete an overturn cycle once every 100 million years. The viscosity of the mantle is temperature-dependent, so it is possible that in early Earth history the mantle may have been able to flow and overturn convectively much more quickly, making convection an even more efficient process and speeding the rate of plate tectonic processes.

There is currently on ongoing debate and research relating to the style of mantle convection in the Earth. The relatively heterogeneous upper mantle extends to a depth of 416 miles (670 km), where there is a pronounced increase in seismic velocities. The more homogeneous lower mantle extends to the D″ region at 1,678 miles (2,700 km), marking the transition into the liquid outer core. One school of mantle convection thought suggests that the entire mantle, including both the upper and the lower parts, is convecting as one unit. Another school posits that the mantle convection is divided into two layers, with the lower mantle convecting separately from the upper mantle. A variety of these models, presently held by the majority of geophysicists, is that there is two-layer convection, but that subducting slabs can penetrate the 415-mile (670-km) discontinuity from above, and that mantle plumes that rise from the D″ region can penetrate the 415-mile (670-km) discontinuity from below.

The shapes taken by mantle convection cells include many possible forms reflected to a first order by the distribution of subduction zones and midocean ridge systems. The subduction zones mark regions of downwelling, whereas the ridge system marks broad regions of upwelling. Material is upwelling in a broad cell beneath the Atlantic and Indian Oceans and downwelling in the circum-Pacific subduction zones. There is thought to be a large plumelike "superswell" beneath part of the Pacific that feeds the East Pacific rise. Mantle plumes that originate from the deep mantle punctuate this broad pattern of upper-mantle convection, and their plume tails are distorted by flow in the convecting upper mantle.

The pattern of mantle convection and transfer of internal energy to the surface deep in geological time is uncertain. Some periods such as the Cretaceous seem to have had much more rigorous mantle convection and surface volcanism. More or different types or rates of mantle convection may have helped to allow the early Earth to lose heat more efficiently. Some computer models allow periods of convection dominated by plumes, and others dominated by overturning planiform cells similar to the present Earth. Some models suggest cyclic relationships, with slabs pooling at the 425-mile (670-km) discontinuity, then suddenly all sinking into the lower mantle, causing a huge mantle overturn event. Further research is needed on linking the preserved record of mantle convection in the deformed continents to help interpret the past history of convection.

EXTERNAL ENERGY SOURCES AND VARIATIONS: THE SUN AND CHANGES IN EXTERNAL ENERGY CAUSED BY ORBITAL VARIATIONS

The Sun is the main external contributor of energy to the Earth. The amount of radiation emitted by the Sun is nearly constant on human timescales, but solar emissions vary on 1,500-year timescales. Variations in Earth's orbital parameters around the Sun cause other more significant and systematic changes in the amount of incoming solar radiation. These changes can affect many Earth systems, causing glaciations, global warming, and changes in the patterns of climate and sedimentation. Radiant energy from the Sun drives convection in the atmosphere and oceans, so any changes in the amount of incoming solar radiation affects how these systems work.

Astronomical effects influence the amount of incoming solar radiation; minor variations in the path of the Earth in its orbit around the Sun and the inclination or tilt of its axis cause variations in the amount of solar energy reaching the top of the atmosphere. These variations are thought to be responsible for the advance and retreat of the Northern and Southern Hemisphere ice sheets in the past few million years. In the past 2 million years alone, the ice sheets have advanced and retreated approximately 20 times. The climate record as deduced from ice-core records from Greenland and isotopic tracer studies from deep-ocean, lake, and cave sediments suggest that the ice builds up gradually over periods of about 100,000 years, then retreats rapidly over a period of decades to a few thousand years. These patterns result from the cumulative effects of different astronomical phenomena.

Several orbital variations are involved in changing the amount of incoming solar radiation, or external energy delivered to the Earth. The Earth follows an elliptical orbit around the Sun; the shape of this elliptical orbit is its eccentricity. The eccentricity changes cyclically with a time period of 100,000 years, alternately bringing the Earth closer to and farther from the Sun in summer and winter. This 100,000-year cycle is about the same as the general pattern of glaciers advancing and retreating every 100,000 years in the past 2 million years, suggesting that this is the main cause of variations within the present-day ice age.

The Earth's axis is presently tilting by 23.5°N/S away from the orbital plane, and the tilt varies between 21.5°N/S and 24.5°N/S. The tilt changes by plus or minus 1.5°N/S from a tilt of 23°N/S every 41,000 years. When the tilt is greater, there is greater seasonal variation in temperature.

Wobble of the rotation axis describes a motion much like a top rapidly spinning and rotating with a wobbling motion, such that the direction of tilt toward or away from the Sun changes, even though the amount of tilt stays constant. This wobbling phenomenon is known as precession of the equinoxes; it places different hemispheres closer to the Sun in different seasons. Presently the precession of the equinoxes are such that the Earth is closest to the Sun during the Northern Hemisphere winter. This precession changes with a double cycle, with periodicities of 23,000 years and 19,000 years.

Because each of these astronomical factors acts on different timescales, they interact in a complicated way, known as Milankovitch cycles, after the Yugoslav Milutin Milankovitch who first analyzed them in the 1920s. Understanding these cycles enables one to predict where the Earth's climate is heading, whether the planet heading into a warming or cooling period, and whether civilization needs to plan for sea-level rise, desertification, glaciation, sea-level drops, floods, or droughts.

EXTERNAL ENERGY-DRIVEN PROCESSES IN THE ATMOSPHERE AND OCEANS

The atmosphere constitutes a sphere around the Earth consisting of a mixture of gases held in place by gravity. The atmosphere is divided into several layers, based mainly on the vertical temperature gradients that vary significantly with height. The lower 36,000 feet (11 km) of the atmosphere is the troposphere, where the temperature generally decreases gradually, at about 70°F per mile (21°C per km), with increasing height above the surface. This is because the Sun heats the surface that in turn warms the lower part of the troposphere. External energy received from the Sun drives processes in the atmosphere.

The atmosphere is always moving, because more of the Sun's heat is received per unit area at the equator than at the poles. The heated air expands and rises to where it spreads out, then cools and sinks, and gradually returns to the equator. This pattern of global air circulation forms Hadley cells that mix air between the equator and midlatitudes. Hadley cells are belts of air that encircle the Earth, rising along the equator, dropping moisture as they rise in the Tropics. As the air moves away from the equator at high elevations, it cools, becomes drier, then descends at 15–30°N and S latitude, where it either returns to the equator or moves toward the poles. The locations of the Hadley Cells move north and south annually in response to the changing apparent seasonal movement of the Sun. High-pressure systems form where the air descends, characterized by stable clear skies and intense evaporation, because the air is so dry. Another pair of major global circulation belts is formed as air cools at the poles and spreads toward the equator. Cold polar fronts form where the polar air mass meets the warmer air that has circulated around the Hadley Cells from the Tropics. In the belts between the polar front and the Hadley Cells, strong westerly winds develop. The position of the polar front and extent of the west-moving wind is controlled by the position of the polar jet stream (formed in the upper troposphere), which is partly fixed in place in the Northern Hemisphere by the high Tibetan Plateau and the Rocky Mountains. Dips and bends in the jet stream path are known as Rossby waves; these partly determine the location of high- and low-pressure systems. Rossby waves tend to be semistable in different seasons and have predictable patterns for summer and winter. If the pattern of Rossby waves in the jet stream changes significantly for a season or longer, it may cause storm systems to track to different locations from normal, causing local droughts or floods. Changes in this global circulation may also change the locations of regional downwelling, cold dry air. This can cause long-term drought and desertification. Such changes may persist for periods of several weeks, months, or years, and may explain several of the severe droughts that have affected Asia, Africa, North America, and elsewhere.

Circulation cells similar to Hadley Cells mix air in middle to high latitudes, and between the poles and high latitudes. The effects of the Earth's rotation modify this simple picture of the atmosphere's circulation. The Coriolis effect describes how any freely moving body in the Northern Hemisphere veers to the right, and toward the left in the Southern Hemisphere. The combination of these effects forms the familiar trade winds, including the easterlies and westerlies, and doldrums.

Like the atmosphere, the ocean is constantly in motion, driven by external energy from the Sun. Ocean currents are defined by the movement paths of water in regular courses, controlled by the wind and thermohaline forces across the ocean basins. Shallow currents are driven primarily by the wind, but are systematically deflected by the Coriolis force to the right of the atmospheric wind directions in the Northern Hemisphere, and to the left of the prevailing winds in the Southern Hemisphere. Shallow water currents therefore tend to be oriented about 45° from the predominant wind directions.

Deep-water currents are driven primarily by thermohaline effects, or the movement of water driven by differences in temperature and salinity. The temperature differences are ultimately controlled by different amounts of solar radiation received by different parts of the global oceans. The Atlantic and Pacific Ocean basins both show a general clockwise rotation in the Northern Hemisphere, and a counterclockwise spin in the Southern Hemisphere, with the strongest currents in the midlatitude sectors. The pattern in the Indian Ocean is broadly similar but seasonally different and more complex because of the effects of the monsoon. Antarctica is bound on all sides by deep water and has a major clockwise current surrounding it, the Antarctic circumpolar current, lying between 40° and 60° south. This strong current moves at 1.6–5 feet per second (0.5–1.5 m/s), and has a couple of major gyres in it at the Ross Ice Shelf and near the Antarctic Peninsula. The Arctic Ocean has a complex pattern, because it is sometimes ice covered and is nearly completely surrounded by land, with only one major entry and escape route east of Greenland, called Fram Strait. Circulation patterns in the Arctic Ocean are dominated by a slow, 0.4–1.6-inch per second (1–4 cm/s) transpolar drift from Siberia to the Fram Strait, and by a thermohaline-induced anticyclonic spin known as the Beaufort gyre that causes ice to pile up on the Greenland and Canadian coasts. Together the two effects in the Arctic Ocean bring numerous icebergs into North Atlantic shipping lanes and send much of the cold deep water around Greenland into the North Atlantic Ocean basin.

See also ATMOSPHERE; BLACK SMOKER CHIMNEYS; CLIMATE; CLIMATE CHANGE; CONVECTION AND THE EARTH'S MANTLE; EARTH; EARTHQUAKES; GEOLOGICAL HAZARDS; HURRICANES; HYDROSPHERE; ICE AGES; MANTLE PLUMES; PLATE TECTONICS; RADIOACTIVE DECAY.

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environmental geology

environmental geology Environmental geology is an applied interdisciplinary science focused on describing and understanding human interactions with natural geologic systems. It also includes the field of earth system science, where different systems of the lithosphere, biosphere, hydrosphere, and atmosphere interact, and changes in one system are seen to influence the other systems.

Environmental geology is a diverse field that includes studies of the hydrological system and how humans' use of water resources affects the system. It also encompasses studies of natural resources such as petroleum and other hydrocarbons and how their use affects the natural environment.

Many of the applications of environmental geology have to do with defining and mitigating the effects of exposure to natural hazards, such as floods, earthquakes, volcanoes, tsunamis, landslides, and coastal hazards. In other situations the field of environmental geology is considered more restricted, referring to the environmental issues arising from specific geologic materials such as radon, groundwater contaminants, asbestos, and lead. This discussion focuses on the later aspects of environmental geology, specifically, the processes that concentrate hazardous elements in soils and how these elements make it into homes and human bodies, and harm individuals and entire populations.

HAZARDOUS ELEMENTS, MINERALS, AND MATERIALS

Many of the more than 100 naturally occurring elements are toxic to humans in high doses, and some occur in high concentrations in the soil. The same elements may be beneficial or even necessary in small, dilute doses and pose little or no threat in intermediate concentrations. Most elements show similar toxicity effects on humans, although not all are toxic in high doses. Understanding the effects of trace elements in the environment on human health is the realm of the huge and rapidly growing field of medical geology.

Natural processes in soils in many places on the planet concentrate potentially hazardous geologic materials. The health hazards posed by these elements depend on the way humans interact with their environment, which can vary significantly among different cultures. Primitive cultures that live off the land are more susceptible to hazards and disease associated with contaminated or poor water quality, toxic elements in plants harvested from contaminated soils, and insect- and animal-borne diseases associated with unsanitary environments. In contrast, more developed societies are more likely to be affected by air pollution, different types of water pollution, and indoor pollution such as radon exposure. Some diseases reflect a complex interaction among humans, insects or animals, climate, and the natural concentration of certain elements in the environment. For instance, schistosomiasis-bearing snails are abundant in parts of Africa and Asia where natural waters are rich in calcium derived from soils, but in similar climates in South America, the condition is rare. It is thought that this difference is because the waters in South America are calcium-poor, whereas disease-bearing snails need calcium to build their shells.

All life-forms are composed of a few basic elements, including hydrogen, carbon, nitrogen, oxygen, phosphorus, sulfur, chlorine, sodium, magnesium, potassium, and calcium. Some other elements are important for life, as they play vital roles in controlling how tissues and organs function. Trace element metals are present in very dilute quantities in our bodies; some known to be important for life functions include fluorine, chromium, manganese, iron, cobalt, copper, zinc, selenium, molybdenum, and iodine. Other elements accumulate in tissue as it ages, but their function, and whether they are beneficial or detrimental, is yet to be determined. These age elements include nickel, arsenic, aluminum, and barium.

The distribution of elements in the natural environment is complex and may be changed by many different processes. Geologic processes such as volcanism may concentrate certain elements in some locations even to ore grade or unhealthy levels. When these igneous rocks are weathered, the concentrations of specific elements may be increased or decreased in the soil horizon, depending on the element, climate, and other factors. After this, biological processes may further concentrate elements. Together, leaching and accumulation of elements during soil formation, biological concentration, and many other processes may concentrate or disperse elements that may be harmful to humans.

Some minerals are hazardous when exposed in the natural environment or when extracted in mining operations. In particular, selenium, asbestos, silica, coal dust, and lead can be harmful when inhaled or when present in high concentrations in the environment.

Iodine

Iodine occurs naturally in the geologic environment and is released from rocks by weathering. It is readily soluble in water, so most iodine makes its way to the sea after it is leached from bedrock or soil. A deficiency of iodine in the body can lead to several adverse health effects including thyroid disease and goiter.

There is a strong correlation between the geography of occurrence of thyroid disease and a deficiency of iodine in the environment. Much of the northern half of the conterminous United States has soils low in iodine; this same region yields most of the thyroid disease cases in the United States.

Selenium

Selenium is one of the most toxic elements known in the environment. Like most elements, selenium is needed in small concentrations for normal biological functions. Concentrations of 0.04 to 0.1 parts per million are healthy, but any larger concentration is toxic.

Selenium is produced naturally by volcanic activity, and it is usually ejected as small particles that fall out near volcanoes, causing higher concentrations near volcanic vents. Selenium in natural soils ranges from 0.1 parts per million to more than 12,000 parts in organic-rich soils. Selenium exists in insoluble form in acidic soils and in soluble form in alkaline soils. Biological activity may also concentrate selenium. Some plants take up soluble selenium and concentrate it in their structures. The efficiency of this process depends on the form in which it exists (soluble or insoluble) in the environment. Selenium is also concentrated in human tissue to about 1,000 times the background level in freshwater. It is also concentrated by up to 2,000 times the natural background level in marine fish.

The concentration of selenium in biological material has persisted through geological time; thus many coals and fossil fuels are also rich in selenium. Burning coal releases large amounts of selenium into the atmosphere, and this selenium then rains down on the landscape.

Asbestos

Asbestos was widely used as a flame retardant in buildings through the mid-1970s, and it was present in millions of buildings in the United States. It was also used in vinyl flooring, ceiling tiles, and roofing

Tailings from the Comstock mine of the late 1800s *(Russell Shively, Shutterstock, Inc.)*

LOVE CANAL IS NOT FOR HONEYMOONERS

Love Canal is not a place many people would choose to visit on a honeymoon. Love Canal was a quiet neighborhood in Niagara Falls, New York, that became infamous as one of the most horrific toxic waste dumps in the country. The history of Love Canal began in the 1890s, when entrepreneur William T. Love envisioned building a canal that would connect the two levels of the Niagara River, above and below the falls, for generating electricity and, eventually, as a shipping canal. He dug about a mile (1.6 km) of the canal, with a channel about 15 feet (5 m) wide and 10 feet (3 m) deep, before his scheme failed and the project was abandoned. Eventually his land was sold to the city of Niagara Falls, which used the undeveloped land as a landfill for chemical waste. The canal was thought to be appropriate for this use since the geology consisted of impermeable clay and the area was rural. The area was then acquired by Hooker Chemical, which continued its use as a toxic chemical landfill, dumping more than 22,000 tons of toxic waste into the site from 1942 to 1952, until the canal was full. Then the site was backfilled with four feet (1.2 m) of clay and closed.

As the city of Niagara Falls expanded, land was needed for many purposes, including schools. The local school board attempted to buy the land from Hooker Chemical, but the chemical company initially refused, showing the school board that the site was a toxic waste dump. The board eventually won and purchased the site for one dollar, with a release to Hooker Chemical that the company had explained about the toxic wastes and would not be liable for deaths or resultant health problems. A school was then built directly on top of the landfill. During construction the contractors broke through the clay seal under the landfill that was intended to prevent leakage of the waste into the local groundwater. Soon after this in 1957, the city constructed sewers for a neighborhood growing around the school, and in doing so broke through the seal of the landfill again, after which chemicals began seeping out of the old canal in more locations. Further construction of roads in the area restricted some of the groundwater flow, and water levels in the old canal rose above ground level, so the site became an elongate pond.

Children in the area began showing health problems, including epilepsy, asthma, and infections, but the source was not known. In 1978 parents in the community united under the leadership of a concerned mother, Lois Gibbs, and discovered that their community was built on top of a huge toxic waste dump. Their complaints of sick children, chemical odors, and strange substances oozing out of the ground were at first ignored by local officials, but were heard in 1979 by the Environmental Protection Agency (EPA). The EPA documented a disturbingly high incidence of miscarriages, nervous disorders, cancers, and strange birth defects. More than half of the children born in Love Canal between 1974 and 1978 were documented as having birth defects, some of which were severe. Many legal and political battles ensued, with the residents unable to sell their homes. Both the city and Hooker Chemical (by that time a subsidiary of Occidental Petroleum) denied liability, and the health problems persisted. Residents were losing the legal battles against the local government and the chemical company.

On August 7, 1978, President Jimmy Carter declared a federal emergency at Love Canal, and began relocating residents living closest to the canal. Carcinogens such as benzene were discovered in the groundwater around the site, and many residents showed a range of severe health effects, including leukemia. On May 21, 1980, President Carter declared a wider state of emergency and relocated more than 800 families away from the site. This and a similar chemical waste catastrophe at Times Beach, Missouri, led Congress to pass the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), commonly known as the Superfund Act. The EPA sued Occidental Petroleum, which paid $129 million in compensation, and a permanent Superfund Act has helped hold many polluters liable for similar negligent acts that have polluted the nation's land and groundwater resources since that time.

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material. New construction no longer uses asbestos since scientists discovered that it might cause certain types of disease, including asbestosis (pneumoconiosis), a chronic lung disease. Asbestos particles lodge in the lungs, then the lung tissue hardens around the particles, decreasing lung capacity. This decreased lung capacity causes the heart to work harder and can lead to heart failure and death. Virtually all deaths from asbestosis can be attributed to long-term exposure to asbestos dust in the workplace before environmental regulations governing asbestos were put in place. A less common disease associated with asbestos is mesothelioma, a rare cancer of the lung and stomach linings. Asbestos has become one of the most devastating occupational hazards in U.S. history, costing billions of dollars for cleaning up asbestos in schools, offices, homes, and other buildings. Approximately $3 billion a year is currently spent on asbestos removal in the United States, and many older building still contain large amounts of asbestos in their insulation, panels, and other building materials.

Asbestos is actually a group of six related minerals, all with similar physical and chemical properties. Asbestos includes minerals from the amphibole and serpentine groups that are long and needle-shaped; this makes it easy for them to lodge in the lungs. The Occupational Safety and Health Administration (OSHA) defined asbestos as having dimensions greater than 5 micrometers (0.002 inches) long, with a length-to-width ratio of at least 3:1. The minerals in the amphibole group included in this definition are grunerite (known also as amosite), reibeckite (crocidolite), anthophyllite, tremolite, and actinolite, and the serpentine group mineral that fits the definition is chrysotile. Almost all of the asbestos used in the United States is chrysotile (known as white asbestos), and about 5 percent of the asbestos used was crocidolite (blue asbestos) and amosite (brown asbestos). There is currently considerable debate among geologists, policymakers, and health officials on the relative threats from different kinds of asbestos.

In 1972 OSHA and the U.S. government began regulating the acceptable levels of asbestos fibers in the workplace. The Environmental Protection Agency (EPA) agreed and declared asbestos a Class A carcinogen. The EPA composed the Asbestos Hazard Emergency Response Act, which was signed by President Reagan in 1986. OSHA gradually lowered the acceptable limits from a preregulated estimate of greater than 4,000 fibers per cubic inch (1,600 fibers per cubic centimeter) to four particles per cubic inch (1.6 fibers per cubic centimeter) in 1992. Responding to public fears about asbestosis, Congress passed a law requiring that any asbestos-bearing material that appeared to be visibly deteriorating must be removed and replaced by nonasbestos-bearing material. This remarkable regulation has caused billions of dollars to be spent on asbestos removal, which in many cases may have been unnecessary. Asbestos can be harmful only as an airborne particle, and only long-term exposure to high concentrations leads to disease. In some cases it is estimated that removing the asbestos caused the inside air to become more hazardous than before removal, as the remediation can cause many small particles to become airborne and fall as dust throughout the building.

Asbestos fibers in the environment have led to serious environmental disasters, as the hazards were not appreciated during early mining operations before the late 1960s. One of the worst cases occurred in the town of Wittenoom, Australia. Crocidolite was mined in Wittenoom for 23 years between 1943 and 1966, and the mining was largely unregulated. Asbestos dust filled the air of the mine and the town, and the 20,000 who lived in Wittenoom breathed the fibers daily in high concentrations. More than 10 percent, or 2,300 people, who lived in Wittenoom have since died of asbestosis, and the Australian government has condemned the town and is burying the asbestos in deep pits to rid the environment of the hazard.

In the United States W. R. Grace and Company in Libby, Montana, afflicted hundreds of people with asbestos-related diseases through its mining operations. Vermiculite was mined at Libby from 1963 to 1990 and shipped to Minneapolis to make insulation products, but the vermiculite was mixed with the tremolite (amphibole) variety of asbestos. In 1990 the EPA tested residents of Libby and found that 18 percent who had been there for at least six months had various stages of asbestosis and that 49 percent of the W. R. Grace mine employees had asbestosis. The mine was closed, and Libby is now a Superfund site, where the EPA has determined that toxic wastes were dumped and must be cleaned up. The problem was not limited to Libby, however; 24 workers at the processing plant in Minneapolis have since died from asbestosis, and one resident who lived near the factory also died.

Silica and Coal Dust

Other minerals can be hazardous if made into small airborne particles that can lodge in the lungs. As with asbestos, both silica- and coal-mining operations release large amounts of dust particles into the air, also known, respectively, as quartz dust and coal dust. Workers exposed to these dusts are at risk for diseases broadly similar to asbestosis.

Quartz dust is commonly produced during rock drilling and sandblasting operations. These practices produce airborne particles of various sizes, the largest of which are naturally filtered by hair and mucous membranes during inhalation. Some of the smallest particles can work their way deeply into the lungs, however, and get lodged in the air sacs of the alveoli, where they can do great harm. When small particles get trapped in the air sac, the lungs react by producing fibrolitic nodules and scar tissue around the trapped particles, reducing lung capacity in a disease called silicosis. This disease is easily preventable by simply wearing a respiratory mask when exposed to silica fibers, although this is not yet a common practice.

Coal dust has presented a long-term health problem in the United States and elsewhere, with underground coal miners being at high risk for developing the disease. Mining operations inevitably release fine particles of coal into the air. These particles may lodge in the lungs to cause a myriad of diseases including chronic bronchitis and emphysema, collectively known as black lung disease. The longer a miner works underground, the greater the risk of developing black lung disease. Miners who work underground for fewer than 10 years have about a 10 percent chance of developing these symptoms, whereas miners who have worked underground for more than 40 years have a 60 percent chance of developing black lung disease.

Lead

Lead is a metalliferous element used primarily for pipes, solder, batteries, bullets, pigments, radioactivity shields, and wheel weights. Lead is a known environmental hazard, and ingestion of large amounts can lead to developmental problems in children, including retardation, brain damage, and birth defects. It may also lead to kidney failure, multiple sclerosis, and brain cancer. Some researchers speculate that the fall of the Roman Empire was partly caused by lead poisoning. The Romans drank a lot of wine, and lead was concentrated at several different steps in the process used to make wine then. The upper class also drank from lead cups, and water was pumped into their homes in lead pipes. It is thought that lead poisoning contributed to brain damage, retardation, and the high incidence of birth defects among the Romans. These ideas are supported by the high content of lead measured in the remains of some exhumed Roman citizens. Remarkably, the lead content of ice cores from Greenland representing the Roman Empire period (500 B.C.E–300 C.E.) also preserve about four times the normal level of lead, reflecting the increased mining and use of lead by the Romans.

Lead is present in the natural environment in several different forms. Galena is the most common ore mineral, forming shiny cubes with a silvery “lead” color. Lead is not generally hazardous in its natural mineral form, but it becomes hazardous when mined and released from smelters as particulates, when leached from pipes or other fixtures, or when released into the air from automobile fumes. These processes can lead to high concentrations of native lead in soils, streams, and rivers. Lead may then be taken up by plants or aquatic organisms and thus enter the food chain, where it can do great damage. Lead paint is also a great hazard in many homes in the United States, as lead was used as a paint additive until the 1970s. Paint in many older homes is peeling and ingested by infants, and paint along window frames is turned into airborne dust when windows are opened and closed. Environmental regulations in many states now require the removal of lead paint from homes upon the sale or leasing of properties.

The largest lead smelter in the United States, in Herculaneum, Missouri, brings an example of the legacy of lead mining. Herculaneum is located about 30 miles south of St. Louis, in the heart of the nation’s largest lead deposit belt and has been the site of mining operations for generations. The problem in Herculaneum is that the town’s smelter releases 34 tons of emissions per year (reduced from 800 tons per year a generation ago), including fine-grained lead dust. This rains down on the local community, and the local street dirt has been tested and found to contain 30 percent lead. Signs on the streets in town warn children not to play in the streets, curbs, or sidewalks, and parents are vigilant in attempting to keep the dust off toys, shoes, and out of the food and water supply. All their efforts were not enough, though, and the State of Missouri has replaced the soil on 535 properties contaminated by lead. Many of the children and adults in the town are suffering the effects of lead poisoning, with retardation, stunted growth, hearing loss, and clusters of brain cancer and multiple sclerosis in town. One-quarter of all the children in the town tested positive for lead poisoning in 2001. Lead contamination had long been suspected in Herculaneum, but it was not until 2002 that the federal government stepped in. In January 2002 the EPA initiated a large-scale relocation program, initially moving 100 families with young children or pregnant women to safer locations. This may be only the beginning of the end, as government officials have been attempting to shut down the Doe Run Lead Smelter and perhaps relocate the 2,800 families remaining in Herculaneum, Missouri.

Radon

Many U.S. homes accumulate radon. Radon is a poisonous gas and a by-product of radioactive decay of the uranium decay series. A heavy gas, radon is a serious indoor hazard in every part of the country. It tends to accumulate in poorly ventilated basements and well-insulated homes built on specific types of soil or bedrock rich in uranium minerals. Radon is known to cause lung cancer; since it is odorless and colorless, it can go unnoticed in homes for years. But the radon hazard is easily mitigated and homes can be made safe once the hazard is identified.

Uranium is a radioactive mineral that spontaneously decays to lighter daughter elements by losing high-energy particles at a predictable rate known as a half-life. The half-life specifically measures how long it takes for half of the original or parent element to decay to the daughter element. Uranium decays to radium through a long series of steps with a cumulative half-life of 4.4 billion years. During these steps intermediate daughter products are produced, and high-energy particles including alpha particles, consisting of two protons and two neutrons, are released. This produces heat. The daughter mineral radium is itself radioactive, and it decays with a half-life of 1,620 years by losing an alpha particle, thus forming the heavy gas radon. Radon escapes from the minerals and ground and makes its way to the atmosphere, where it is dispersed unless it gets trapped in homes. If it gets trapped, it can be inhaled and do damage. Radon is a radioactive gas that decays with a half-life of 3.8 days, producing daughter products of polonium, bismuth, and lead. If this decay occurs while the gas is in someone's lungs, then the solid daughter products become lodged in the lungs. This is how radon damage is initiated. Most of the health risks from radon are associated with the daughter product polonium, which is easily lodged in lung tissue. Polonium is radioactive, and its decay and emission of high-energy particles in the lungs can damage lung tissue, eventually causing lung cancer.

The concentration of radon among geographic regions and in specific places in those regions varies tremendously. There is also a great variation in the concentration of the gas at different levels in the soil, home, and atmosphere. This variation is related to the concentration and type of radioactive elements present at a location. Radioactivity is measured by the picocurie (pCi), which is approximately equal to the amount of radiation produced by the decay of two atoms per minute.

Soils have gases trapped between the individual grains that make up the soil, and these soil gases have typical radon levels of 20 pCi per liter to 100,000 pCi per liter, with most soils in the United States falling in the range of 200–2,000 pCi/L. Radon can also be dissolved in groundwater with typical levels falling between 100–2 million pCi/Liter. Outdoor air typically has 0.1–20 pCi/Liter, and radon inside homes ranges from 1–3,000 pCi/Liter, with 0.2 pCi/Liter being typical.

Formation and Movement of Radon Gas

There are many natural geologic variations that lead to the complex distribution of hazardous radon. One of the main variables controlling radon concentration at any site is the initial concentration of the parent element uranium in the underlying bedrock and soil. If the underlying materials have high concentrations of uranium, it is more likely that homes built in the area may have high concentrations of radon. Most natural geologic materials contain a small amount of uranium, typically about 1–3 parts per million (ppm). The concentration of uranium is typically about the same in soils derived from a rock as in the original source rock. However, some rock (and soil) types have much higher initial concentrations of uranium, ranging up to and above 100 ppm. Some of the rocks that have the highest uranium content include some granites, some volcanic rocks (especially rhyolites), phosphate-bearing sedimentary rocks, and the metamorphosed equivalents of all of these rocks.

As the uranium in the soil gradually decays, it leaves its daughter product, radium, in concentrations proportional to the initial concentration of uranium. The radium then decays by forcefully ejecting an alpha particle from its nucleus. This ejection is an important step in the formation of radon, since every action has a reaction. In this case the reaction is the recoil of the nucleus of the newly formed radon. Most radon remains trapped in minerals once it forms. But if the decay of radium happens near the surface of a mineral, and if the recoil of the new nucleus of radon is away from the center of the grain, the radon gas may escape the bondage of the mineral. It will then be free to move in the intergranular space between minerals, soil, or cracks in the bedrock, or become absorbed in groundwater between the mineral grains. Less than half (10–50 percent) of the radon produced by decay of radium actually escapes the host mineral. The rest is trapped inside where it eventually decays, leaving the solid daughter products behind as impurities.

Once the radon is free in the open or water-filled pore spaces of the soil or bedrock, it may move rather quickly. The exact rate of movement is critical to whether or not the radon enters homes, because radon does not stay around for long with a half-life of only 3.8 days. The rates at which radon moves through a typical soil depend on how much pore space there is in the soil (or rock), how connected these pore spaces are, and the exact geometry and size of the openings. Radon moves quickly through very porous and permeable soils such as sand and gravel, but moves very slowly through less permeable materials such as clay. Radon also moves very quickly through fractured material, whether bedrock, clay, or concrete.

Considering how the rates of radon movement are influenced by the geometry of pore spaces in a soil or bedrock underlying a home, and how the initial concentration of uranium in the bedrock determines the amount of radon available to move, it becomes apparent that there should be a large variation in the concentration of radon from place to place. Homes built on dry, permeable soils can accumulate radon quickly because it can migrate through the soil quickly. Conversely, homes built on impermeable soils and bedrock are unlikely to concentrate radon beyond their natural background levels.

Radon becomes hazardous when it enters homes and becomes trapped in poorly ventilated or well-insulated areas. Radon moves up through the soil toward places with greater permeability. Home foundations are often built with a porous and permeable gravel envelope surrounding the foundation to allow for water drainage. This also focuses radon movement and brings it close to the foundation, where the radon may enter through small cracks in the concrete, seams, spaces around pipes, sumps, and other openings, as well as through the concrete that may be moderately porous. Most modern homes intake less than 1 percent of their air from the soil. Some homes, however, particularly older homes with cracked or poorly sealed foundations, low air pressure, and other entry points for radon, may intake as much as 20 percent of their internal air from the soil. These homes tend to have the highest concentrations of radon.

Radon can also enter the home and body through groundwater. Homes that rely on well water may be taking in water with high concentrations of dissolved radon. This radon can then be ingested or released from the water by agitation in the home. Radon is released from high-radon water by simple activities such as showers, washing dishes, or running faucets. Radon can also come from municipal water supplies, such as those supplied by small towns that rely on well fields that take the groundwater and distribute it to homes without providing a reservoir for the water to linger in while the radon decays to the atmosphere. Most larger cities, however, rely on reservoirs and surface water supplies, where the radon has had a chance to escape before being used by unsuspecting homeowners.

Radon Hazard Mapping

A greater understanding of the radon hazard risk in an area can be obtained through mapping the potential radon concentrations. This can be done at many scales of observation. Radon concentrations can also be measured locally to determine what kinds of mitigation are necessary to reduce the health risks posed by this poisonous gas.

The broadest sense of risk can be obtained by examining regional geologic maps and determining whether or not an area is located above potential high-uranium-content rocks such as granites, shales, and rhyolites. These maps are available through the U.S. Geological Survey and many state geological surveys. The U.S. Department of Energy has flown airplanes with radiation detectors across the country and produced maps that show the measured surface radioactivity on a regional scale. These maps give a very good indication of the amount of background uranium concentration in an area and thus are related to the potential risk for radon gas.

More detailed information is needed by local governments, businesses, and homeowners to assess whether or not they need to invest in radon remediation equipment. Geologists and environmental scientists can measure local soil radon gas levels using a variety of techniques, typically involving placing a pipe into the ground and sucking out the soil air for measurement. Other devices may be buried in the soil to measure more passively the formation of the damage produced by alpha particle emission. Via such information, the radon concentrations in certain soil types can be established. This information can be integrated with soil characteristic maps produced by the U.S. Department of Agriculture and by state and county officials to make more regional maps of potential radon hazards and risks.

Most homeowners must resort to private measurements of radon concentrations in their homes by using commercial devices that detect radon or measure the damage from alpha particle emission. The measurement of radon levels in homes has become a standard part of home sales transactions, so more data and awareness of the problem have risen in the past 10 years. The remediation of radon problems in homes or businesses with a radon problem has become relatively simple. An engineer or contractor can be hired simply and cheaply (typically less than $1,000 for an average home) to design and build a ventilation system to remove the harmful radon gas, making the air safe to breathe.

SUMMARY

The formation of soil involves the breakdown of solid rock and the removal of the dissolvable component of the rocks, leaving the residual material behind in the soil. This process concentrates certain elements, and some of these can be harmful to human health. Some of the most hazardous elements common in soils include selenium, arsenic, radon, and lead, while mines may expose workers to other harmful elements such as coal dust, silica dust, and asbestos fibers. A variety of health conditions and ailments around the world, generally among poorer populations, are caused by exposure or ingestion of hazardous elements in the soil. Careful monitoring of the concentrations of these elements in developed nations such as the United States has greatly reduced the health threat from them.

See also BEACHES AND SHORELINES; CLIMATE CHANGE; ECONOMIC GEOLOGY; FLOOD; GEOLOGICAL HAZARDS; GLOBAL WARMING; HURRICANES; HYDROCARBONS AND FOSSIL FUELS; HYDROSPHERE; SEA-LEVEL RISE; SUBSIDENCE.

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Eocene The Eocene is the middle epoch of the Paleogene (Lower Tertiary) Period and the rock series deposited during this time interval. The Eocene ranges from 57.8 million to 36.6 million years ago, and is divided from base to top into the Ypresian, Lutetian, Bartonian, and Priabonian ages. The Eocene epoch was named by Charles Lyell in 1833 for mollusk-bearing strata in the Paris basin.

The Tethys Ocean was undergoing final closure during the Eocene, and the main Alpine Orogeny occurred near the end of the epoch. Global climates were warm in the Eocene, and shallow-water benthic nummulites and other large foraminifera became abundant. Mammals became the dominant tetrapods on land, and whales were common in the seas about midway through the epoch. Continental flora included broad-leafed forests in low-latitude forests, and conifers at high latitudes.

See also TERTIARY.

eolian Meaning "of the wind" (after Aeolus, Greek god of the winds), eolian refers to sediments deposited by wind. Loess is fine-grained, windblown silt and dust that covers surfaces and forms thick deposits in some parts of the world, such as Shanxi Province in China. Sand dunes and other forms are moved by the wind and form extensive dune terrains, sand sheets, and sand seas in parts of many deserts.

When wind blows across a surface it creates turbulence that exerts a lifting force on loose, unconsolidated sediment. With increasing wind strengths, the air currents are able to lift and transport larger sedimentary grains, which then bump into and dislodge other grains, causing large-scale movement of sediment by the wind in a process called saltation. When these particles hit surfaces, they may abrade or deflate the surface.

Wind plays a significant role in the evolution of desert landscapes. Wind erodes in two basic ways. Deflation is a process whereby wind picks up and removes material from an area, reducing the land surface. Abrasion occurs when sand and other sizes of particles impact each other. Exposed surfaces in deserts are subjected to frequent abrasion, which is akin to sandblasting.

Yardangs are elongate, streamlined, wind-eroded ridges that resemble an overturned ship's hull sticking out of the water. These unusual features are formed by abrasion, the long-term sandblasting along specific corridors. The sandblasting leaves erosionally resistant ridges but removes the softer material that itself will contribute to sandblasting in the downwind direction, and eventually contribute to the formation of sand, silt, and dust deposits.

Deflation is important on a large scale in places where there is no vegetation, and in some places the wind has excavated large basins known as deflation basins. Deflation basins are common in the United States from Texas to Canada as elongate (several-kilometer-long) depressions, typically only 3–10 feet (1–3 m) deep. In places like the Sahara, however, deflation basins may be as many as several hundred feet deep.

Deflation by wind can move only small particles away from the source since the size of the particle that can be lifted is limited by the strength of the wind, which rarely exceeds a few tens of miles per hour. Deflation leaves behind boulders, cobbles, and other large particles. These get concentrated on the surface of deflation basins and other surfaces in deserts, leaving a surface concentrated in boulders known as desert pavement. Desert pavements are long-term, stable desert surfaces that are not particularly hazardous. The stability of the surface changes when the surface of the desert pavement is broken; for instance, by driving heavy vehicles across the coarse cobbles and pebbles, the gravels get pushed beneath the surface and the underlying sands get exposed to wind action again. Driving across a desert pavement can raise a considerable amount of sand and dust, and if many vehicles drive across the surface, then it can be destroyed, and the whole surface becomes active with sand ripples and dunes forming soon after the surface is disrupted.

Sand dunes are locally important in deserts, and wind is one of the most important processes in shaping deserts worldwide. Shifting sands are one of the most severe geologic hazards of deserts. In many deserts and desert border areas, the sands are moving into inhabited areas, covering farmlands, villages, and other useful land with thick accumulations of sand. This is a global problem, as deserts are currently expanding worldwide.

SAND DUNES

One of the characteristic landforms of deserts is sand dunes, geometrically regular mounds or ridges of sand found in several geological environments, including deserts and beaches. Most people think of deserts as covered with numerous big sand dunes and continual swirling winds of dust storms. Dunes and dust storms are not as common as depicted in popular movies, and rocky deserts are more common than sandy deserts; for instance, only about 20 percent of the Sahara is covered by sand, and the rest is covered by rocky, pebbly, or gravel surfaces. Sand dunes are locally important in deserts, and wind is one of the most significant processes in shaping deserts worldwide. The Institute of Desert Research in Lanzhou, China has recently estimated that in China alone, 950 square miles (2,500 km^2) are encroached on by migrating sand dunes from the Gobi Desert each year, costing the country $6.7 billion per year and affecting the lives of 400 million.

Wind moves sand by saltation—an arching path in a series of bounces or jumps. One can see this often by looking close to the surface in dunes on beaches or deserts. Wind sorts different sizes of sedimentary particles, forming elongate small ridges known as sand ripples, similar to ripples found in streams. Sand dunes are larger than ripples (up to 1,500 feet high, or almost 0.5 km), and are composed of mounds or ridges of sand deposited by wind. These may form where an obstacle distorts or obstructs the flow of air, or they may move freely across much of a desert surface. Dunes have many different forms, but all are asymmetrical. They have a gentle slope that faces into the wind and a steep slope that faces away from the wind. Sand particles move by saltation up the windward side, and fall out near the top where the pocket of low-velocity air cannot hold the sand anymore. The sand avalanches, or slips, down the leeward slope, known as the slip face. This keeps the slope at 30°–34°, the angle of repose. The asymmetry of old dunes is used to determine the directions ancient winds blew.

The steady movement of sand from one side of the dune to the other causes the whole dune to migrate slowly downwind (typically about 80–100 feet per year, or 24–30 m/yr), burying houses, farmlands, temples, and towns. Rates of dune migration of up to 350 feet per year (107 m/yr) have been measured in the Western Desert of Egypt and the Ningxia Autonomous Region of China.

Sand rippled by wind in the Qatari Desert *(photoslb, Shutterstock, Inc.)*

A combination of many different factors leads to the formation of very different types of dunes, each with a distinctive shape, potential for movement, and hazards. The main variables that determine a dune's shape are the amount of sand available for transportation, the strength (and directional uniformity) of the wind, and the amount of vegetation that covers the surface. If there is a lot of vegetation and little wind, no dunes will form. In contrast, if there is little vegetation, a lot of sand, and moderate wind strength (conditions that might be found on a beach), then a group of dunes known as transverse dunes form, with their crests aligned at right angles to the dominant wind direction.

Barchan dunes have crescent shapes and horns pointing downwind; they form on flat deserts with steady winds and a limited sand supply. Parabolic dunes have a U-shape with the U facing upwind. These form where there is significant vegetation that pins the tails of migrating transverse dunes, with the dune being warped into a wide U-shape. These dunes look broadly similar to barchans, except the tails point in the opposite direction. They can be distinguished because in both cases, the steep side of the dune points away from the dominant wind direction. Linear dunes are long, straight, and ridge-shaped, elongated parallel to the wind direction. These occur in deserts with little sand supply and strong, slightly variable winds. Star dunes form isolated or irregular hills where the wind directions are irregular.

SAND SEA

Deserts covering vast expanses covered by thick sands, including sand dunes of several types and by an absence of other geographic features, are known as sand seas, or locally as ergs in the North African Sahara. Interdune areas may be covered by relatively flat tabular sand sheets, or even evaporite basins (sabkhas). Sand seas are abundant in parts of the Sahara of North Africa, the Namib of southern Africa, the Rub‘ al-Khali (Empty Quarter) of Arabia, the Great Sandy Desert of Australia, the Gobi Desert of Asia, and the Nebraska Sand Hills of Nebraska.

Sand seas form where the velocity of the transporting wind decreases, dropping its load. The decreased velocity may be caused by a number of factors, including in topographic lows, or adjacent to topographic barriers, such as mountains that cut across the direction of sand transport. A striking example of this process is found in the Wahiba Sand Sea of Oman. Here the Eastern Hajar Mountains terminate the northward-flowing Wahiba sands, and an intermittent river system at the base of the mountains removes sand that gets close to the mountain front, carrying it to the coast of the Arabian Sea. Longshore transport then carries this sand southward where winds pick it up from beaches and cause it to reenter the Wahiba sand sheet in the south, forming a sort of sand gyre. Sand seas may also form where a large body of water intercepts drifting sand, or where the sand is carried into shifting climate zones where the wind strength decreases.

Surface features in sand seas include bed forms of a variety of scales ranging from several different types of ripples that may be up to an inch (several cm) high, to dunes that are typically up to 300 feet (100 m) tall, to huge bedforms called draa that are giant dunes up to 1,650 feet (500 m) tall, with wavelengths of up to several kilometers. These bedforms are typically superimposed on each other, with dunes migrating over and on top of draa and several different sets of ripples migrating over the dunes. The wind directions inferred from the different sets may also be different, with ripples reflecting the most recent winds, dunes the dominant winds over different seasons, and draa reflecting the very long-term direction of wind in the basin.

See also DESERTS.

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erosion Erosion encompasses a group of processes that cause Earth material to be loosened, dissolved, abraded, or worn away and moved from one place to another. These processes include weathering, dissolution, corrosion, and transportation. There are two main categories of weathering: physical and chemical processes. Physical processes break down bedrock by mechanical action of agents such as moving water, wind, freeze-thaw cycles, glacial action, forces of crystallization of ice and other minerals, and biological interactions with bedrock such as penetration by roots. Chemical weathering includes the chemical breakdown of bedrock in aqueous solutions. Erosion occurs when the products of weathering are loosened and transported from their origin to another place, most typically by water, wind, or glaciers.

Water is an extremely effective erosional agent, including when it falls as rain and runs across the

Lavaka from severe soil erosion in Ankarafantsika Nature Reserve, Madagascar *(© Pete Oxford/Minden Pictures)*

surface in finger-sized tracks called rivulets, and when it runs in organized streams and rivers. Water begins to erode as soon as raindrops hit a surface—the raindrop impact moves particles of rock and soil, breaking it free from the surface and setting it in motion. During heavy rains, the runoff is divided into overland flow and stream flow. Overland flow is the movement of runoff in broad sheets. Overland flow usually occurs through short distances before it concentrates into discrete channels as streamflow. Erosion performed by overland flow is known as sheet erosion. Streamflow is the flow of surface water in a well-defined channel. Vegetative cover strongly influences the erosive power of overland flow by water. Plants that offer thicker ground cover and have extensive root systems prevent erosion much more than thin plants and crops that leave exposed barren soil between rows of crops. Ground cover between that found in a true desert and in a savanna grassland tends to erode the fastest, while tropical rain forests offer the best land cover to protect from erosion. The leaves and branches break the force of the falling raindrops and the roots form an interlocking network that holds soil in place.

Under normal flow regimes streams attain a kind of equilibrium, eroding material from one bank and depositing it onto another. Small floods may add material to overbank and floodplain areas, typically depositing layers of silt and mud over wide areas. During high-volume floods streams may become highly erosive, even removing entire floodplains that may have taken centuries to accumulate. The most severely erosive floods are found in confined channels with high flow, such as where mountain canyons have formed downstream of many small tributaries that have experienced a large rainfall event. Other severely erosive floods have resulted from dam failures, and in the geological past from the release of large volumes of water from ice-dammed lakes about 12,000 years ago. The erosive power of these floodwaters dramatically increases when they reach a velocity known as supercritical flow, at which time they are able to cut through alluvium like butter and even erode bedrock channels. Supercritical flow cannot be sustained for long periods, as the effect of increasing the channel size causes the flow to self-regulate and become subcritical.

Cavitation in streams can also cause severe erosion. Cavitation occurs when the stream's velocity is so high that the vapor pressure of water is exceeded and bubbles begin to form on rigid surfaces. These bubbles alternately form, then collapse with tremendous pressure, and form an extremely effective erosive agent. Cavitation is visible on some dam spillways, where bubbles form during floods and high-discharge events, but it is different from the more common and significantly less erosive phenomenon of air entrapment by turbulence, which accounts for most air bubbles observed in white-water streams.

Wind is an important but less effective erosional agent than water, particularly in desert or dry environments with exposed soil-poor regolith. Glaciers are powerful agents of erosion, and are thought to have removed hundreds of feet (meters) from the continental surfaces during the last ice ages. These moving masses of ice carve deep valleys into mountain ranges and transport eroded sediments on, within, and in front of glaciers in meltwater stream systems. Glaciers with layers of water along their bases, known as warm-based glaciers, are more effective erosional agents than cold-based glaciers that have no liquid water near their bases. Cold-based glaciers are known from Antarctica.

Mass wasting is considered an erosional process in most definitions, whereas others recognize that mass wasting significantly denudes the surface but classify these sudden events separately. These rapid processes include the transportation of material from one place to another, so they are included here with erosional processes. Most mass wasting processes are related to landslides, debris flows, and rock slides and can significantly reduce the elevation of a region, typically occurring in cycles with intervals ranging from tens to tens of thousands of years.

Humans are drastically altering the planet's landscape, leading to enhanced rates of erosion. Cutting down forests has caused severe soil erosion in Madagascar, South America, the United States, and many other parts of the world. Many other changes are difficult to quantify. Urbanization reduces erosion in some places but enhances it elsewhere. Damming of rivers decreases the local gradient slowing erosion in upland areas, but prevents replenishment of the land in downstream areas. Agriculture and the construction of levees have changed the balance of floodplains. Although difficult to quantify, estimates suggest that human activities in the past couple of centuries have increased erosion rates on average from five times to 100 times previous levels.

See also DESERTS; GLACIER, GLACIAL SYSTEMS; MASS WASTING; WEATHERING.

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Eskola, Pentti (1883–1964) Finnish *Geologist*

Pentti Eelis Eskola was born in Lellainen, Finland, to a farming family. After growing up on the farm he studied at the University of Helsinki, then in 1922 moved to the Carnegie Institution in Washington, D.C., for a postdoctoral position where he conducted experimental studies on the chemical behavior of rock and mineral systems. After two years in Washington Eskola moved back to the University of Helsinki, where he became a chemist before specializing in petrology. He remained a professor for the next 30 years.

Eskola was one of the first geologists to apply physicochemical ideas to the study of metamorphism, and he developed the concept of metamorphic facies. He laid down the foundations for later studies in metamorphic petrology. Throughout his life Eskola was interested in the study of metamorphic rocks, taking an early interest in the Precambrian rocks of Scandinavia and England. Relying heavily on Scandinavian studies, he wanted to define the changing pressure and temperature conditions under which metamorphic rocks were formed. His approach allowed for the comparison of rocks of widely differing compositions in respect of the pressure and temperature under which they had originated.

Pentti Eskola was awarded the Wollaston Medal in 1958, the highest award given by the Geological Society of London, and was honored by many other prizes, including the Penrose and Steinbock medals, and the Vetlesen Prize. Upon his death in 1964 Eskola was given a state funeral.

See also METAMORPHISM AND METAMORPHIC ROCKS; PETROLOGY AND PETROGRAPHY.

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estuary Estuaries are coastal embayments influenced by tides and waves that also have significant freshwater influence derived from a river system that drains into the head of the bay, representing transitional environments between rivers and the sea. Most were formed when sea levels were lower, and rivers carved out deep valleys now flooded by water. They are typically bordered by tidal wetlands and are sensitive ecological zones prone to disturbances by pollution, storms, and overuse by humans. Estuaries accumulate sediment from the river systems from the mainland as well as from the coast, and tend therefore gradually to fill in over time. Each estuary is a unique environment that also preserves a range of water chemistry, reflecting a gradual mixing of the fresh river water from the land and saltwater from the ocean. Saltwater is denser than freshwater, however (having 3.5 percent dissolved salt), and tends in many cases to form a lens that underlies a freshwater cap across the surface of the estuary. The exact nature of the mixing depends on seasonal changes in freshwater influx, basin shape, depth, wave energy, tidal range, and climate. Some estuaries preserve stratified water with saltwater below and freshwater on top, whereas others show complex mixing between the different water types. The biota of estuaries are diverse, reflecting the large range in environments available for different species.

Different parts of estuaries are dominated by river and others by tidal processes. Rivers that enter large estuaries tend to form bayhead deltas that prograde into and may eventually fill the estuary. In other examples, such as Chesapeake Bay, many small rivers may enter the estuary and few have any significant delta, since the river valleys in this system trap most of the stream sediment. Estuaries bordered seaward by barrier islands have much less tidal influence than those with mouths open to the sea, although the tidal range and size and the shape of the estuary also play large roles in determining the strength of tidal versus riverine processes. Tidal-dominated estuaries tend to lack barrier islands at their mouths and exhibit funnel-shaped shorelines that amplify the tides by forcing the incoming tides into progressively more confined spaces. Estuaries that are tidal-dominated with strong tidal currents tend to have well-mixed waters and sandy bottoms, whereas river-dominated estuaries often have stratified water columns and muddy bottoms. Most estuaries exhibit a range of different conditions in different parts—river conditions predominate at the head of the bay, tidal processes dominate at the mouth, and a mixed zone occurs in the middle. An extremely diverse biota inhabits estuaries, with organisms that prefer salty high-energy conditions situated at the mouth of the estuary and freshwater species found near the bayhead. Organisms that tolerate brackish conditions and can adapt to changing salinities and energy are typically found in between in the zone of mixing.

Satellite image of Betsiboka estuary in Madagascar: Waters of estuary run yellow and red from soil washed down by heavy rains. *(M-Sat Ltd./Photo Researchers, Inc.)*

See also BEACHES AND SHORELINES; CONTINENTAL MARGIN; OCEAN BASIN; OCEANOGRAPHY.

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European geology The geology of Europe is dominated by mountains, structures, and basins of the Alpine system in the south, stretching across southern France, northern Italy, then eastward through the Adriatic and Aegean arcs to the Black Sea and finally extending through Turkey to connect with the Himalayan system. This mountain chain formed during the Paleozoic-Cenozoic formation and closure of the Tethys Ocean. The Caspian Sea, on the northern side of the Alpine-Himalayan chain, may represent a piece of oceanic crust trapped during the closure of the Tethys Ocean. Continued closure of the remnants of the Tethys—the Mediterranean—is represented by the active plate margins in southeastern Europe, stretching from the Calabrian arc in Italy, the Hellenic arc in Greece, into the Cyprian arc, which merges with the northern extension of the Dead Sea transform fault. Turkey is moving westward, with the North Anatolian fault as its northern boundary, in response to its escaping from the active collision between Arabia and Asia.

Landsat 5 satellite image of western and central Europe *(M-Sat/Photo Researchers, Inc.)*

The geology of northwestern Europe is delineated largely by the Caledonide system, cutting through the British Isles, well exposed in the Scottish Highlands, and along the northwestern Scandinavian coast. This mountain range formed during the Paleozoic evolution and closure of the Iapetus Ocean. The Baltic shield forms a Precambrian craton in northeastern Europe. It is covered by thick continental and shallow marine deposits, deformed around its edges. The Baltic shield extends through Svalbard Island (Norway) and the Kola Peninsula (Russia) in the north. Geologically the eastern boundary of Europe is considered to be the Ural Mountains, which form a striking north-south line at the edge of the vast East European Plain, which covers deep sections of the Baltic shield and its correlatives.

THE ALPINE MOUNTAIN CHAIN

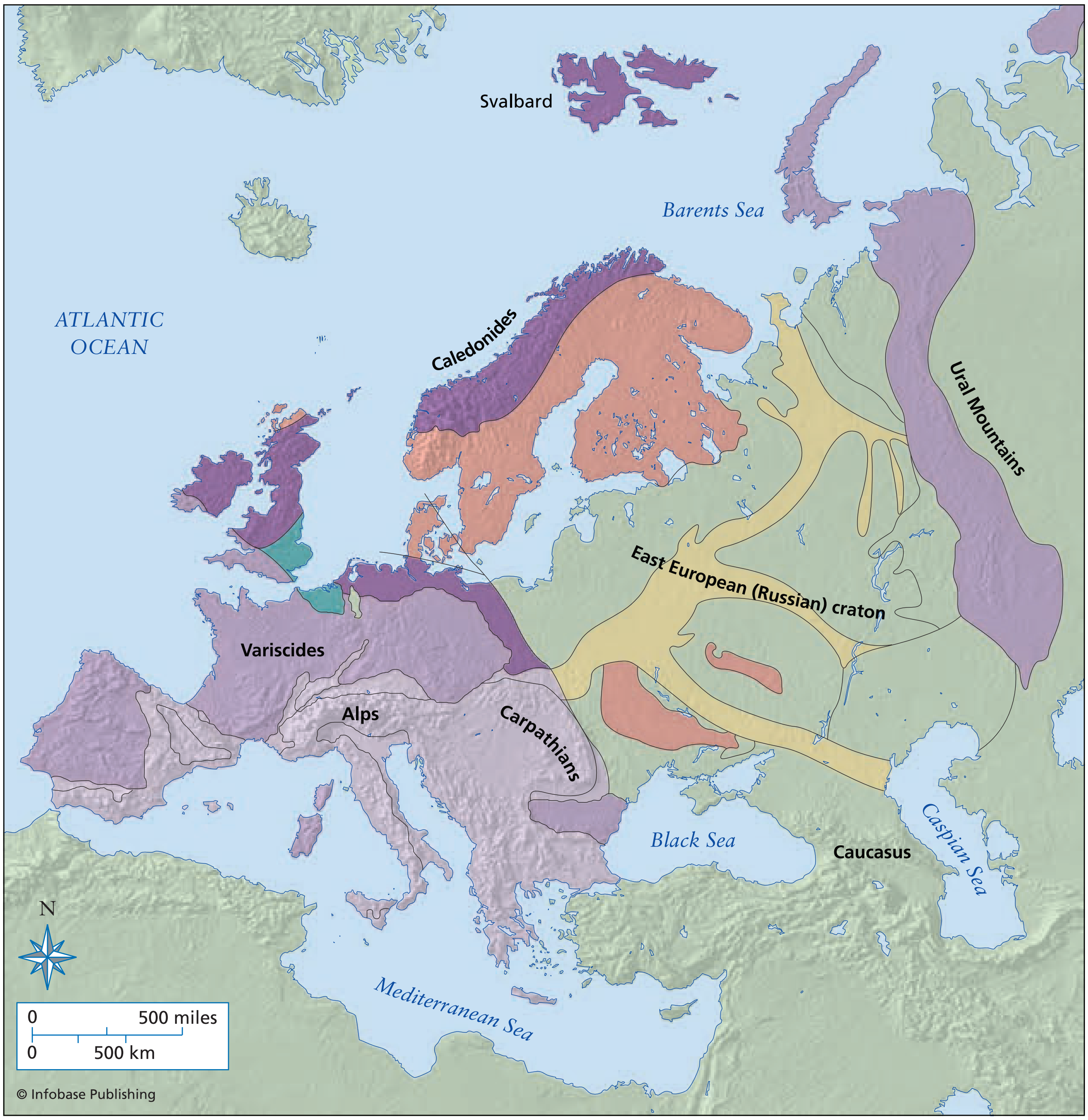
The Alps form an arcuate or curved mountain system of south-central Europe, about 497 miles (800 km) long and 93 miles (150 km) wide, stretching from the French Riviera on the Mediterranean coast, through southeastern France, Switzerland, southwestern Germany, Austria, and former Yugoslavia (Serbia). The snow line in the Alps is approximately 8,038 feet (2,450 m), with many peaks above this permanently snowcapped or hosting glaciers. The longest glacier in the Alps is the Aletsch, but many landforms attest to a greater extent of glaciation in the Pleistocene. These include famous landforms such as the Matterhorn and other horns, arêtes, U-shaped valleys, erratics, and moraines.

The Alps were formed by plate collisions related to the closure of the Tethys Ocean in the Oligocene and Miocene, but the rocks record a longer history of deformation and events extending back at least into the Mesozoic. Closure of the Tethys Ocean was complex, involving contraction of the older Permian-Triassic Paleo-Tethys Ocean at the same time that a younger arm of the ocean, the Neo-Tethys, was opening in the Triassic and younger times. In the late Triassic carbonate platforms covered older evaporites, and these platforms began foundering and were buried under deep-water pelagic shales and cherts in the early Jurassic. Cretaceous flysch covered convergent margin foreland basins, along with felsic magmatism and high-grade blueschist facies metamorphism. Continent-continent collision-related events dominate the Eocene-Oligocene, with the formation of giant fold nappes, thrusts, and deposition of synorogenic flysch. Late Tertiary events are dominated by late orogenic uplift, erosion, and deposition of post-orogenic molasse in foreland basins. Deformation continues through the present, mostly related to postcollisional extension.

CASPIAN SEA, TRAPPED OCEANIC CRUST

The Caspian is a large, shallow, salty inland sea, located between southern Russia, Kazakhstan, Turkmenistan, Iran, and Azerbaijan. It is 144,444 square miles (373,000 km^2), and its surface rests 92 feet (28 m) below sea level. It has a maximum depth of only 3,280 feet (1,000 m) in the south and is very shallow in the north, with an average depth of only 16.5 feet (5 m). Thus changes in the sea level bring large changes in the position of the shoreline. These historical changes in shoreline position are evident in the lowland continuation of the Caspian depression in the Kalymykiya region to the northwest of the sea. More than 75 percent of the water flowing into the Caspian is from the Volga River in the north, draining the western side of the Urals and the European plains. Other rivers that flow into the Caspian include the Ural, Emba, Kura, and Temek, but there is no outlet. The Caucasus Mountains strike into the sea on the west, and the Elbruz Mountains line its southern border.

The Caspian is mineral-rich and blessed with large oil and gas deposits in several regions, and it is one of the most active exploration areas in the world. The Caspian holds an estimated 200 billion barrels of oil, as much as Iraq and Iran combined. Rich petroleum deposits off the Apseran Peninsula on the west led to the development of Baku, Azerbaijan, where the Nobels (including Alfred Nobel, inventor of dynamite and originator of the Nobel prizes) made their fortune at the end of the 19th century. Unfortunately, decades of careless environmental practices associated with Soviet state-run oil extraction has



Simplified geological map of Europe showing the location of the Alps, Caledonides, East European (Russian) craton, Urals, Svalbard, and Caspian Sea

led to widespread pollution and contamination, only recently being cleaned up.

The origin of the Caspian depression is somewhat controversial, but many geologists believe that much of the basin is ocean crust trapped during closure of the Tethys Ocean, then deeply buried by sedimentary sequences that host the many petroleum deposits in the area. The sea is also rich in salt deposits and is extensively fished for sturgeon, although the catches have declined dramatically since the early 1990s. The reasons for the fish decline include loss of spawning grounds, extensive poaching, overfishing, and pollution. A single large (typically up to 15 feet) female beluga sturgeon can weigh 1,300 pounds and carry 200 pounds of roe, which retailers can sell as caviar for $250,000 in the United States.

CALEDONIDES

The Caledonides are an early Paleozoic orogenic belt in north and east Greenland, Scandinavia, and the northern British Isles. The Caledonides were continuous with the Appalachian Mountains before the opening of the Atlantic Ocean, together extending more than 4,101 miles (6,600 km). The history of the opening and closing of the Early Paleozoic Iapetus Ocean and the Tornquist Sea is preserved in the Caledonian-Appalachian orogen, which is one of the best-known and studied Paleozoic orogenic belts in the world. The name is derived from the Roman name for the part of the British Isles north of the firths of Clyde and Forth, used in modern times for Scotland and the Scottish Highlands.

The Paleozoic Iapetus Ocean separated Laurentia (proto-North America) from Baltica and Avalonia, and the Tornquist Sea separated Baltica from Avalonia. The eastern margin of Laurentia has Neoproterozoic and Cambrian rift basins overlain by Cambro-Ordovician carbonate platforms, representing a rifting to trailing or passive margin sequence developed as the Iapetus Ocean opened. Similarly Baltica has Neoproterozoic rift basins overlain by Cambro-Ordovician shelf sequences, whereas the Avalonian margin in Germany and Poland records Neoproterozoic volcanism and deformation, overlain by a Cambro-Silurian shelf sequences, with an arc accretion event in the Ordovician. Gondwana sequences include Neoproterozoic orogens overlain by Ordovician shelf rocks deformed in the Devonian and Carboniferous. Significantly, faunal assemblages in Laurentia, Baltica, Gondwana, and Avalonia all show very different assemblages, interpreted to reveal a wide ocean between these regions in the early Paleozoic. Paleomagnetic data support this conclusion. Middle Ordovician ophiolites and flysch basins on Laurentia and Baltica reflect an arc accretion event in the Middle Ordovician, with probable arc polarity reversal leading to volcanism and thin-skinned thrusting preceding ocean closure in the Silurian.

From these and many other detailed studies, a brief tectonic history of the Appalachian-Caledonide orogen is as follows. Rifting of the Late Proterozoic supercontinent Rodinia at 750–600 million years ago led to the formation of rift to passive margin sequences as Gondwana and Baltica drifted away from Laurentia, forming the wide Iapetus Ocean and the Tornquist Sea. Oceanic arcs collided with each other in the Iapetus in the Cambrian and with the margin of Laurentia and Avalon (still attached to Gondwana) in the Ordovician. These collisions formed the well-known Taconic orogeny on Laurentia, ophiolite obduction, and the formation of thick foreland basin sequences. Late Ordovician and Silurian volcanism on Laurentia reflects arc polarity reversal and subduction beneath Laurentia and Gondwana, rifting Avalon from Gondwana and shrinking the Iapetus as ridges were subducted and terranes were transferred from one margin to another. Avalonia and Baltic collided in the Silurian (430–400 million years ago), and Gondwana collided with Avalon and the southern Appalachians by 300 million years ago, during the Carboniferous Appalachian Orogeny. At this time the southern Rheic Ocean also closed, as preserved in the Variscan Orogen in Europe.

The Caledonides in the Scottish Highlands

Located in the north of the United Kingdom, Scotland includes a variety of generally rugged Lower Ordovician to Archean terranes, dissected by numerous northeast-trending faults that form deep valleys. The coastline of Scotland is highly irregular and has many narrow to wide indented arms of the sea known, respectively, as lochs and firths. The Hebrides, Orkney, and Shetland Islands lie off the coast of northern Scotland. The Southern Uplands form a series of high, rolling, grassy and swampy hills known locally as moors, underlain by a series of strongly folded and faulted Ordovician and Silurian strata. These are separated from the Midland valley by the Southern Uplands fault, an Early Paleozoic strike-slip fault later converted to a normal fault. The Midland Valley includes thick deposits of the Devonian-Carboniferous Old Red Sandstone deposited under continental conditions. The Highland Boundary fault separates the Midlands Valley from the Grampian Highlands, where Precambrian to Early Paleozoic metamorphic and igneous rocks of the Dalradian and Moine Groups are exposed in rugged mountains. The Great Glen fault, a Late Paleozoic left-lateral fault, separates the Grampian Highlands from the Northern Highlands, where Grenvillian-age Moine and Archean Lewisian rocks are exposed. The tallest mountain in Scotland, Ben Nevis (4,406 feet; 1,343 meters) is located in the highlands. The Moine thrust forms the northwestern edge of the Caledonian Orogen, with Archean and Proterozoic rocks of the Lewisian gneisses forming the basement of the orogen.

The oldest rocks exposed in the Scottish Highlands are the Archean (3 billion years old) through Lower Proterozoic Lewisian gneisses formed during the Scourian tectonic cycle, found principally in the Hebrides Islands and the Northern Highlands. The Late Archean gneisses include tonalitic and gabbroic types, with rare ultramafic-mafic plutonic units, probably formed in a volcanic arc setting. Other shallow-shelf metasedimentary rocks including quartzites, limestones, and pelites were metamorphosed to granulite facies at 2.7 billion years ago.

The Invernian tectonic cycle in the Early Proterozoic deformed large tracts of the Scourian gneisses into steep-limbed, west-northwest trending linear structures, accompanied by retrograde amphibolite facies metamorphism. Mafic dike swarms intruded at 2.2 and 1.91 billion years ago, and are not metamorphosed. Post–1.9 billion-year-old Laxfordian cycle events include the formation of shear zones and intrusion of granite plutons near 1.72 billion years ago and a cessation of events by 1.7 billion years ago.

The Moinian Assemblage is a Middle Proterozoic (older than 730 million years, and probably older than 1 billion years) group of pelites and psammites complexly folded into fold interference patterns and metamorphosed to amphibolite facies. Late Proterozoic (970–790 million years old) rocks include two sequences of red beds including the Stoer, Sleat, and Torridon Groups. These groups include conglomerates, siltstones, and sandstones more than a mile (several kilometers) thick in most places, and up to four miles (6 km) thick in a few places. Most of these Late Proterozoic rocks were probably deposited in fluvial or deltaic environments, perhaps in fault-bounded troughs along a continental margin.

The Dalradian Supergroup is found within the Caledonian Orogen south of the Great Glen Fault and north of the Highland Boundary Fault. The Dalradian is more than 12 miles (20 km) thick and is divided into four groups. The lowermost Grampian Group includes shallow to deepwater sandstones and graywackes, overlain by shallow shelf rocks including limestones, shales, and sandstones of the Appin Group. The succeeding Lochaber Group includes sandstones, siltstones, and carbonates deposited in a deltaic environment. The top of the Dalradian consists of the Argyll Group, including a glacial tillite, limestones, and deeper-water graywackes, interbedded with Late Proterozoic (595 million-year-old) basalts. The Dalradian rocks were deformed into large nappe structures in the Late Proterozoic Grampian Orogeny and metamorphosed to the amphibolite facies.

The Paleozoic Era in the Scottish Highlands is marked by a basal transgression of the Durness sequence of shallow-marine quartzites with peculiar trace fossils called skolithos, and limestones onto the Torridonian and Lewisian gneisses. The basal transgressive sequence is about 1,100 feet (350 m) thick, overlain by Lower Cambrian through Ordovician shelf limestones. This sequence is correlated with the basal Cambrian-Ordovician shelf sequence in the Appalachian Mountains, as the Scottish Highlands was linked with Greenland and the Laurentian margin in the Early Paleozoic. However, there is no correlation of rocks of the Scottish Highlands with rocks south of the Highland Boundary Fault, supporting tectonic models that suggest that the southern British Isles were separated from Scotland by a major ocean, known as Iapetus. In the latest Cambrian or Early Ordovician times the region was affected by main phases of the Caledonian Orogeny, known as the Athollian Orogeny, in the Scottish Highlands. Several generations of folds and regional metamorphism are related to the closure of the Iapetus Ocean along the Highland Boundary Fault, where an oceanic assemblage of cherts, pillow lavas, serpentinites, and Cambro-Ordovician limestones are preserved in a complexly deformed wedge of rock known as a mélange. These events associated with the Early Paleozoic closure of the Iapetus Ocean are correlated with the Taconic and Penobscottian Orogenies in the northern Appalachians. In the Southern Uplands a tectonically complex wedge of imbricated slivers of Ordovician-Silurian deepwater turbidites, shales, and slivers of pillow lavas may represent an oceanic accretionary wedge associated with continued closure of additional segments of the Iapetus Ocean.

The Moine thrust zone in the Northern Highlands formed at the end of the Silurian and places the Caledonian orogenic wedge over the foreland rocks of the Lewisian and Dalradian sequences to the northwest. The Moine thrust is one of the world's classic zones of imbricate thrust tectonics, clearly displaying a sole thrust and imbricate splays, thrust-related folds, klippen, and windows. These structures formed as a Late-Caledonian effect of convergence and shortening between the formerly separated margins of the Iapetus Ocean and placed the orogen wedge allochthonously over basement rocks of the Laurentian margin.

The Old Red Sandstone is a Silurian-Devonian sequence of conglomerates, sandstones, siltstones, shales, and bituminous limestones that is up to 10,000 feet (3,048 m) thick. These rocks represent fluvial-delataic to lacustrian deposits eroded from the southeast and are interpreted as a molasse sequence representing denudation of the Caledonides. The Old Red Sandstone is loosely correlated with the Devonian Catskill Mountains deltaic complex in the Appalachians, representing erosion of the Appalachian Mountains after the Devonian Acadian Orogeny. Carboniferous deposits in Scotland include shales, coal measures, basalts, and limestones, deposited in deltaic environments mostly in the Midland Valley. Devonian through Carboniferous sinistral strike-slip faults cut many parts of the Scottish Highlands and are associated with Hercynian tectonic events in Europe, and the Acadian-Appalachian Orogenies in the Appalachians.

BALTIC SHIELD

The Baltic (Fennoscandian) shield is an Archean craton divided into three distinct parts. The northern, Lapland-Kola province consists mainly of several previously dispersed Archean crustal terranes that together with the different Paleoproterozoic belts have been involved in a collisional-type orogeny at 2.0 to 1.9 billion years ago. A central, northwest-trending segment known as the Belomorian mobile belt is occupied by assemblages of gneisses and amphibolites. This part of the Baltic shield has experienced two major orogenic periods, in the Neoarchean and Paleoproterozoic. The Neoarchean period included several crust-forming events between 2.9 and 2.7 billion years ago that can be interpreted in terms of first subduction-related and later collisional orogeny. In the end of the Paleoproterozoic at 1.9–1.8 billion years ago, strong structural and thermal reworking occurred during an event of crustal stacking and thrusting referred to as the Svecofennian Orogeny, caused by overthrusting of Lapland granulite belt onto the Belomorian belt. Although the Svecofennian high-grade metamorphism and folding affected all of the belt, its major Neoarchean crustal structure reveals that early thrust and fold nappes developed by 2.74–2.70 billion years ago. In contrast, the Karelian Province displays no isotopic evidence for strong Paleoproterozoic reworking. The Karelian craton forms the core of the shield and largely consists of volcanic and sedimentary rocks (greenstones) and granites/gneisses that formed between 3.2 and 2.6 billion years ago and were metamorphosed at low-grade. Local synformal patches of Paleoproterozoic 2.45 to 1.9 billion-year-old volcano-sedimentary rocks unconformably overlie the Karelian basement. To the southwest of the Archean Karelian craton the Svecofennian domain represents a large portion of Paleoproterozoic crust developed between 2.0 and 1.75 billion years ago.

Although tectonic settings of the Karelian Archean greenstone belts are still a matter of debate, there are some indications that subduction-accretion processes similar to modern-day convergent margins operated at least since 2.9 billion years ago. But a large involvement of deep mantle–plume derived oceanic plateaus in Archean crustal growth processes remains questionable in respect to subduction style.

Baltic Shield on the Kola Peninsula

The Kola Peninsula occupies 50,000 square miles (129,500 km^2) in northwestern Russia as an eastern extension of the Scandinavian peninsula, on the shores of the Barents Sea, east of Finland and north of the White Sea. Most of the peninsula lies north of the Arctic Circle. The peninsula is characterized by tundra in the northeast, and taiga forest in the southwest. Winters are atypically warm and snowy for such a northern latitude because of nearby warm Atlantic Ocean waters, and warm summers are filled with long daylight hours.

The Kola Peninsula is part of the Archean Baltic shield, containing medium to high-grade mafic and granitic gneisses including diorite, tonalite, trondhjemite, granodiorite, and granite. Metasedimentary schist, metapelitic gneiss, quartzite, and banded-iron formation known as the Keivy Assemblage form linear outcrop belts in the eastern part of the Kola Peninsula. Mafic/ultramafic greenstone belts and several generations of intrusions are found on the peninsula; these may correlate with ophiolitic rocks of the North Karelian greenstone belts farther south in the Baltic shield. Metamorphism is mostly at amphibolite facies but locally reaches granulite facies, and deformation is complex with abundant fold interference patterns and early isoclinal folds possibly associated with early thrust faults. The Kola schist belts are intruded by several generations of mafic to granitic intrusions.

Baltic Shield and Caledonides on Svalbard and Spitzbergen Island

Spitzbergen is the largest island (15,000 square miles; 40,000 km^2) of Svalbard, a large island territory of Norway located in the Arctic Ocean. The islands are on the Barents Shelf, bounded by the Greenland Sea on the west and the Arctic Ocean on the north. The entire Svalbard archipelago was originally referred to as Spitzbergen, but in 1940 the name was changed to Svalbard, and "Spitzbergen" was reserved for the largest island of the archipelago that also includes the islands of Nordaustlandet, Edgeoya, Barentsoya, Prins Karls Forland, and many smaller islands. About half of the island of Spitzbergen is covered by permanent ice and glaciers, and many deeply incised fjords rise to a level of about 3,200 feet (1,000 m), the present height of a flat erosion surface known as a peneplain that has rebounded since the Cenozoic. Since the entire archipelago lies so far north between 76°–81°N, the Sun remains above the horizon from late April through late August but remains below the horizon in winter months. The warm Gulf Stream current has a moderating effect on the climate.

The Svalbard archipelago is well exposed and preserves a complex history of Archean and younger events. The island chain is broken into three main terranes separated by north-south striking faults. The eastern terrane has a basement of Archean through Proterozoic gneisses and amphibolites overlain by psammitic and pelitic schists and marbles that are approximately 1,750 million years old, related to the Baltic shield. These are overlain by pelites, psammites, and felsic volcanics that are about 970 million years old, overlain by 900–800 million-year-old quartzites, silts, and limestones. A Vendian group of pelites and glacial tillites formed during the Varanger glaciation. These are overlain by Cambro-Ordovician carbonates, correlated with similar rocks of eastern Greenland. Mid-Paleozoic tectonism is related to the closure of the Iapetus Ocean during the Caledonian Orogeny, known locally as the Friesland Orogeny. West-vergent fold and thrust structures formed in the Middle and Late Ordovician, whereas late tectonic batholiths intruded in the Silurian through Early Devonian. North-south–striking mylonite zones are concentrated on the western side of the terrane and indicate sinistral transpressive strains.

The central terrane contains a basement of mainly Proterozoic and possible Archean igneous gneisses, overlain by dolostones and Varanger tillites, overlain by Ediacarian phyllites. These are followed by Cambro-Ordovician carbonates. Devonian strata on Svalbard are exposed only in the central terrane and include Old Red Sandstone facies dated by identification of fossil fish remains, similar to that of Scotland. These beds are associated with sinistral transpressive tectonics with the opening of pull-apart basins and the deposition of conglomerates, sandstones, and shales in fluvial systems in these basins. Devonian and Mesozoic strata are folded and show eastward vergence.

The western terrane has a gneissic Proterozoic basement, overlain by Varanger tillites interbedded with mafic volcanics, and overlain by Ediacarian fauna. It is thought that this terrane correlates more with sequences on Ellsemere Island than in the rest of Svalbard or Greenland, so it was probably brought in later by strike-slip faulting. Deformation in Early Ordovician times in the western terrane is linked with subduction tectonics, which may have continued to the Late Ordovician. Later deformation occurred in the Devonian, possibly associated with the Ellsemerian Orogeny.

Some models for the tectonic evolution of Svalbard invoke more than 600 miles (1,000 km) of sinistral strike-slip displacements in the Silurian-Late Devonian on the north-south faults, bringing the eastern terrane into juxtaposition with central Greenland. This motion is associated with the formation of the pull-apart basins filled by the Old Red Sandstone in the central terrane.

In the Carboniferous through Early Eocene most of Svalbard was relatively stable and experienced platform sedimentation, continuous with that of northern Greenland and the Sverdrup basin of northern Canada. Early Carboniferous anhydrites, breccias, conglomerates, sabkha deposits, and carbonates form the basal 3,000 feet (1,000 m) of the section, and these grade up into 1,500 feet (450 m) of fine-grained siliciclastic rocks, cherts, and glauconititic sandstones. Mesozoic strata include more than 8,000 feet (2,500 m) of interbedded deltaic and marine deposits. A Late Cretaceous period of nondeposition was followed by the deposition of nearly 5,000 feet (1,500 m) of deltaic sandstones, shales, and marine beds in the Paleocene and Early Eocene.

In the Eocene western Spitzbergen collided in a dextral transpressional event with the northeast margin of Greenland, forming folds, thrusts, and, later, normal faults along the western coast of the island. Small pull-apart basins formed during this event and are filled by sediments derived from the contemporaneous uplifted fold belt. Erosion and peneplaination in the Oligocene through Holocene formed the flat surface evident across the archipelago today, with Quaternary glaciations depressing the crust. Postglacial rebound, plus thermal uplift associated with the opening of the Arctic Ocean, and the Norwegian and Greenland basins has uplifted the land surface in recent times. Quaternary flood basalts in the northern part of Svalbard are associated with these extensional basin-forming events.

See also ACCRETIONARY WEDGE; CAMBRIAN; CARBONIFEROUS; CONTINENTAL MARGIN; CONVERGENT PLATE MARGIN PROCESSES; DEFORMATION OF ROCKS; DIVERGENT PLATE MARGIN PROCESSES; METAMORPHISM AND METAMORPHIC ROCKS; OPHIOLITES; ORDOVICIAN; OROGENY; PALEOZOIC; PLATE TECTONICS; PRECAMBRIAN; SILURIAN; STRUCTURAL GEOLOGY; SUBDUCTION, SUBDUCTION ZONE; TRANSFORM PLATE MARGIN PROCESSES.

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evolution The fossil record indicates that organisms have changed through time, and these changes are best explained by the theory of evolution. Organic evolution is the cumulative and irreversible change of organisms through time, and results of this process explain the distribution and diversity of life throughout Earth history.

Species are a group of interbreeding populations reproductively isolated from other groups. An adaptation of a species is a change that occurs in one species to make the organism better able to cope with its environment. Genetic mutations can result in positive or negative changes to species, but negative changes tend to cause extinction, whereas positive changes tend to help species survive. The theory of evolution explains how these changes occur, the role of the environment, and how these changes help the organism to survive. To understand evolution and the history of theories of evolution, it is necessary to also understand the differences between ontogeny, the development of an individual organism from young to old age (as from a tadpole to a frog), and phylogeny, the evolutionary history of an organism.

In his 1809 treatise *Philosophie Zoologique* Jean-Baptiste Lamarck (1744–1829), a French naturalist, soldier, and academic, proposed a theory of evolution, stating that the fundamental aspect of nature is change, and "life is a stream of gradual complication." Lamarck was one of the first scientists to suggest that the environment can give rise to change in animals, driving evolution. He suggested that if the environment changes, this would force habits of organisms to change, and if these habits persist they would give rise to new characteristics. The most famous example he used to illustrate his case was the giraffe, which, he suggested, evolved from a horse, the descendants of whose necks became gradually stretched to reach leaves high on trees. Lamarck believed that the natural system was constantly replenished by spontaneous generation from inorganic material, and that the youngest organisms were the simplest, and the oldest were the most complex. Lamarckian evolution is not believed by scientists today, since no experimental or other evidence was ever found to support this type of cause-and-effect evolution. But Lamarck is remembered for his contribution of the idea of the inheritance of acquired characteristics.

Charles Robert Darwin (1809–82) was an English naturalist widely regarded as the father of the modern theory of evolution. Some of his most important work stems from his voyage on the research vessel HMS *Beagle* from 1831 to 1836, when he traveled around the world studying and collecting plants, animals, rocks and minerals. In his studies of modern and ancient biological assemblages Darwin noted that the number of individuals in a given population remains relatively constant and that predator-prey relationships within the environment ensure that only those individuals best suited for life in that environment survive. Many individuals within a population are born with inherited characteristics that prevent them from surviving in that environment, and they die. Darwin called this process natural selection, and noted that with time the process makes the entire population of that species better suited for its environment. Darwin noted that as the environment changes, "only the fittest will survive." However, as with Lamarckian evolution, the mechanism for Darwinian evolution was lacking, and no explanation for acquiring advantageous adoptions was known.

In 1869 the Austrian scientist and priest Gregor Johan Mendel (1822–84) described a system of genes, or heritable units, by which characteristics are transmitted from parents to offspring. Mendel became known as the father of genetics, and led to the study of heredity by 1910, after a period of 40 years in which the significance of his work was not appreciated. After this delay it was realized that new characteristics, or mutations, arise completely at random, and are related to chemical changes in DNA. These were thought to be caused by one of the three following mechanisms:

- imperfect replication of DNA during cell division
- physical alteration of segments of DNA by twisting, breaking, or reversed strands
- alteration by an external force such as a virus or radiation

Many mutations turn out to be harmful, causing death, while others cause very small, almost imperceptible changes.

The next major step in understanding evolution was made in 1869 by Ernst Haeckel (1834–1919), a German biologist, naturalist, physician, and professor who documented a direct relationship between the development of an embryo and the history of the group to which it belonged. Haeckel suggested that the "ontogeny [development of the individual] is a short history of the phylogeny [history of the race]." Haeckel further postulated that evolution proceeded by adding stages to the end of an individual's life. But scientists now know that evolutionary stages can be added at any time during ontogeny but are more typically added during the early stages.

EVOLUTION IN THE FOSSIL RECORD

The vast expanses of time needed to test models of evolution are provided by the fossil record, which extends back hundreds of millions of years for complex organisms, and billions of years for simple organisms. The first example of evolution described from the geologic record was in 1869, when German geologist Wilhelm Heinrich Waagen (1841–1900), who studied Jurassic ammonites, published his classic *Die Formenreihe des Ammonites subradiatus* (The Sequence of Form of the Ammonite's Subradiatus), where he showed a series of very small changes gradually accumulated to make much larger changes that contributed to a gradual evolution of the species. Also in 1869 British biologist Thomas H. Huxley (1825–95) proposed a model for the linear evolution of horses, suggesting that smaller forms evolved into larger forms, a model that was later proven too simple and incorrect. Huxley proclaimed himself an *agnostic* (meaning that claims of metaphysical relationships and proving the existence of and establishing relationships with God are unattainable ideals), a term that has stuck to this day, and that caused him to have many debates with the religious community.

The period 1870–80 saw intense fossil collecting and description in attempts to document evolution in the fossil record. Many collectors, biologists, and naturalists were attempting to test the idea of phyletic gradualism, that many groups of organisms began as simple, unspecialized forms, and gradually became more specialized and larger. Huxley's model for the evolution of the horse was a prime example. The fossil record showed the opposite to be true, however, and revealed that most major groups appear suddenly in the record and many are already highly advanced with their first appearance. The model of phyletic gradualism obviously needed to be replaced with a theory that could explain the sudden appearance of many highly specialized species.

Fossil Neanderthal skull (found at La Ferrassie) and Cro-Magnon skull of similar antiquity *(John Reader/ Photo Researchers, Inc.)*

Ideas of evolution experienced a new revolution in 1972, with the publication of a landmark paper by American paleontologists Niles Eldredge (b. 1943–) and Stephen Jay Gould (1941–2002) proposing an alternative mechanism for evolution called punctuated equilibrium. The basic idea of this model is that new characteristics (mutations) may be found in small populations of the main group of a species, and these tend to become isolated near the geographic periphery of the main species range. These can eventually become completely isolated and evolve into a new species reproductively isolated from the original group. Yet the chances of survival and of preserving this new group in the geological record are small. In the case that they do survive, environmental conditions may be such that they could (in rare circumstances) be adapted to fill suddenly an ecological niche, especially if the original group becomes extinct or less able to survive in the same ecological niche under the changing environmental conditions.

Understanding evolution requires a systematic method to classify and describe organisms and fossils. All life-forms are classified into the hierarchy of Kingdom-Phyla-Class-Order-Families-Genera-Species. Most organisms are classified based on their morphology, or general physical appearance. For this it is common to search for homologous features, which are the same on two different organisms or species, and suggest that the two had a common ancestor. In most cases organisms diverge in their characteristics with evolution, but in some cases there is a convergence of characteristics between different species with different ancestors, resulting in similar or analogous features. This phenomenon can happen from similar environmental stimuli, such as the development of advantageous wings in birds and in insects.

Cladistics is the hierarchical classification of species based on the evolutionary ancestry of the species, and uses cladograms (family trees) to show the relationships of organisms through the evolutionary chain. If there is information on the cladogram about the time or age of the different species or their branching, then this cladogram becomes a phylogenetic tree. The general principles of cladistics operate by comparing specialized characteristics of organisms and placing organisms with the same derived characteristics on the branch (clade).

Studies of phylogenetic trees and fossil assemblages have shown that at certain times in the geological past large numbers of new species and genera have suddenly appeared and rapidly filled ecological niches. These intervals are called adaptive radiations, and are thought to occur in response to rapid changes in external factors such as environmental differences caused by plate tectonic upheavals and supercontinent rearrangements. One famous example of such an adaptive radiation is the Cambrian explosion, during which large numbers of complex new organisms suddenly appeared in the geologic record, filling many ecological niches, soon after the breakup of the supercontinent Gondwana. Adaptive radiations are often terminated by periods of mass extinction.

See also DARWIN, CHARLES; HISTORICAL GEOLOGY; MASS EXTINCTIONS; STRATIGRAPHY, STRATIFICATION, CYCLOTHEM.

FURTHER READING

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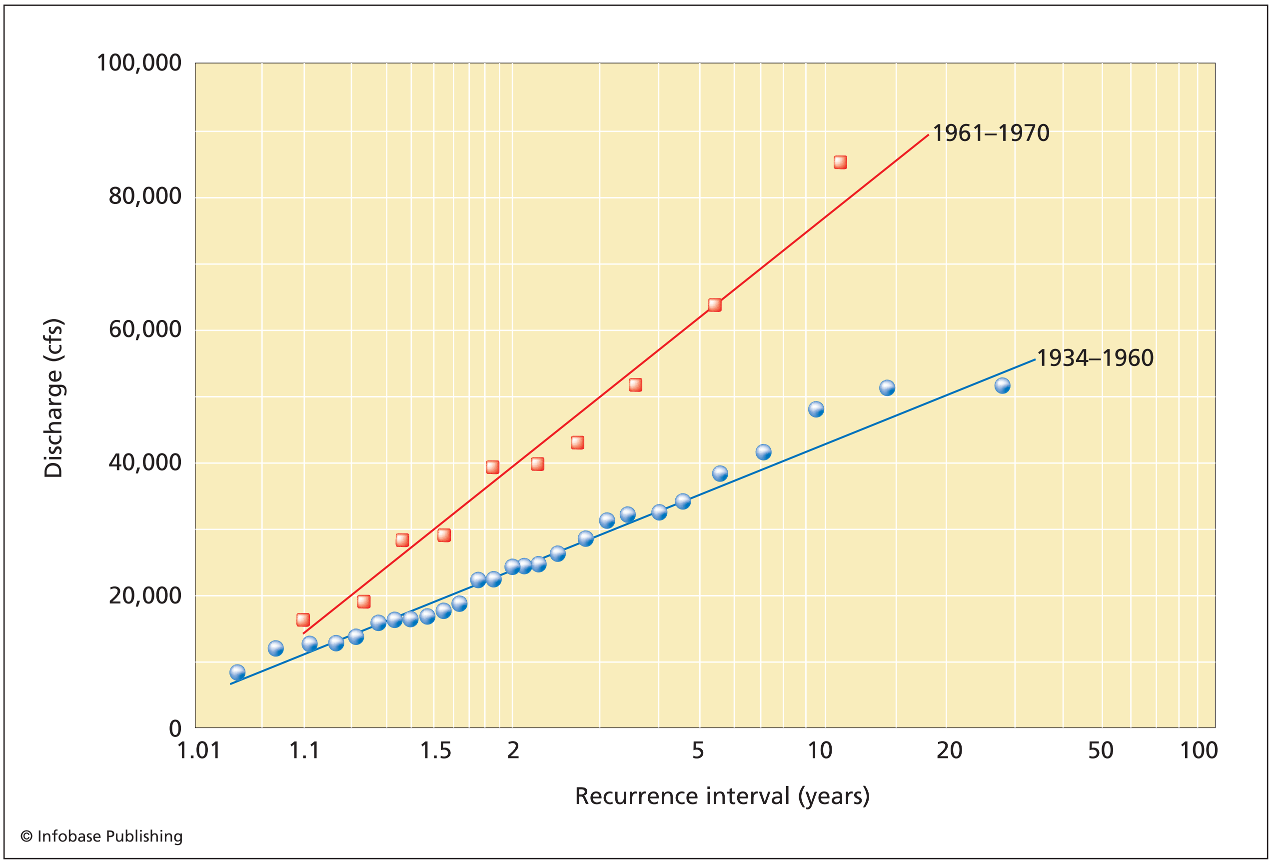
flood A flood occurs when too much water is in one place at one time. When rains, heavy snowmelts, or combinations of these events bring more water than normal into populated areas, floods result. Many floods cause significant damage and destruction because over the past couple of centuries many cultures have moved large segments of their populations onto floodplains, the flat areas adjacent to rivers that naturally flood. Ancient cultures used these floods and the rich organic mud that covered the floodplains during the floods as natural fertilizers for farmlands. Now that many towns, cities, and other population centers have been built on floodplains, people regard these natural flood cycles as disasters. In fact, about 9 out of every 10 disaster proclamations by the president of the United States is for flood disasters, typically to provide funds to those who have built on floodplains. Additionally, many types of natural vegetation have been removed from hillsides, particularly in urban areas. This reduces the amount of infiltration of water into the hillsides and increases the amount and rate of surface runoff, amplifying the danger of floods.

Floods come in many forms, including flash floods where huge volumes of water come rushing out of mountain canyons, carrying mud, boulders, and every other kind of debris washing into valleys and lowlands. Some floods are associated with coastal storms that bring high tides into coastal lowlands and back up river systems far across deltas and coastal plains. Many regions experience slowly rising, long-lasting regional floods associated with spring snowmelts and unusually heavy rains that can last for weeks or months. Some high-latitude climate zones also experience floods in association with the spring breakup of ice on rivers. As the ice melts, blocks move downriver, occasionally jamming and forming ice dams that can cause rapidly rising ice-cold floodwater to cover the river floodplains.

RIVER FLOODS AND FLOOD FREQUENCY

Seasonal variations in rainfall cause stream discharge to rise and sometimes overflow the stream's banks. Both stream discharge and velocity increase during floods, so at floods the streams carry larger particles. Many of the most dramatic changes in river channels occur during floods—meander channels may be cut off, new channels may form, natural levees may be breached, and, occasionally, the river may abandon one channel altogether in favor of another. Floods have a probable interval of recurrence for floods of specific magnitude. Small floods occur quite often, typically every year. Larger floods occur less frequently, and the largest floods occur with the longest time interval between them. The time interval between floods of a specific discharge is known as the recurrence interval, and this is commonly cited using statistics for the 50-year flood, 100-year flood, 500-year flood, and so on.

Curves of the discharge versus recurrence interval can be drawn for every stream and river to determine its characteristic flooding frequency. Knowing how likely it is that a flood of a certain height will recur within a certain time frame is important information for everyone living near a stream or on a river floodplain. For instance, if a flood of 150 cubic feet/second (4.25 m^3/s) covered a small town with 10 feet (3 m) of water 30 years ago, is it safe to build a new housing development on the floodplain on the outskirts of town? Using the flood frequency curve for that river,



Flood frequency curve for two different periods of different climates, along a river in Africa. The recurrence time (horizontal axis) represents how often a flood with a specific volume of water (vertical axis, showing discharge in cubic feet per second) occurs at a location along a river. Note that the river had a dry climate from 1934 to 1960, and floods were not as large or as frequent as in the wetter period from 1961 to 1970. Changes in climate can severely impact the predicted frequency of floods. *(Data from the Ministry of Water Development, Kenya)*

planners could determine that floods of 150 cubic feet/second (4.25 m^3/s) are expected on average every 40 years, and floods of two times that magnitude are expected every 100 years. Planners and insurers might (in the best of situations) conclude from that information that it is unwise to build extensively on the floodplain—the new community should be located on higher ground.

Understanding flood frequency and the chances of floods of specific magnitude occurring along a river is also essential for planning many other human activities. Engineers must determine how much water bridges and drainage pipes must be built to handle and how to plan for land use across the floodplain. In many cases bigger, more expensive bridges should be built, even if it seems unlikely that a small stream will ever rise high enough to justify such a high bridge. In other cases structures are built with a short lifetime of use expected, and planners must calculate whether the likelihood of flood warrants the extra cost of building a flood-resistant structure.

EXAMPLES OF DIFFERENT TYPES OF FLOODS

Floods are the most common natural hazard and have also proven to be the deadliest and costliest of all natural disasters in history. Individual floods have killed upwards of a million people in China on several occasions, and cause billions of dollars of damage annually in different parts of the world. The risk of flooding increases with time as many countries are allowing settlements on floodplains and even encouraging commercial and residential growth on floodplains known to experience floods at frequencies of every several to every couple of hundred years. As world population continues to grow and people move into harm's way on floodplains, this problem will only worsen. Further, as the climate changes, some areas will experience more rainfall while others experience drought, so areas that may be relatively safe on floodplains now may be frequently inundated with floodwaters in the near future. Development of floodplains should not proceed without proper scientific analysis of the risks. In most cases floodplains should be preserved as natural areas or used for farming, but should not be the sites of major commercial or residential development.

Several kinds of floods affect different areas, act on different timescales, and present different types of hazards. Floods associated with hurricanes and tidal surges in coastal areas can cause extreme damage during these coastal storms. Rare, large thunderstorms in mountains and canyon territory typically cause a second type of flood, known as a flash flood. These floods can move into areas as a mud- and debris-laden wall of water, wiping out buildings and towns within a few seconds to minutes. Prolonged rains over large drainage basins cause a third category of floods, called regional floods. A final type of flood occurs in areas where rivers freeze over. In cold climate zones the annual spring breakup can cause severe floods, initiated when blocks of ice jam up behind islands, beneath bridges, or along river bends. These ice dams can create severe floods, causing the high spring waters to rise quickly, bringing the ice-cold waters into low-lying villages on floodplains. When ice dams break up, the force of the rapidly moving ice is sometimes enough to cause severe damage, knocking out bridges, roads, and homes. Ice-dam floods are fairly common in parts of New England, including New Hampshire, Vermont, and Maine. They are also common across much of Alaska and Canada, but the floodplains in these areas tend to be less developed so the floods pose fewer hazards to humans.

COASTAL STORMS AND STORM SURGES

Coastal areas affected by cyclones and hurricanes are prone to flooding by storm surges associated with these storms. Storm surges, formed by water pushed ahead of storms, typically move on land as exceptionally high tides in front of these severe ocean storms. Storm surges are one of the major, most unpredictable hazards to people living along coastlines.

When hurricanes, cyclones, or extratropical lows (also known as coastal storms and northeasters) form, they rotate and the low pressure at the centers of the storms raises the water several to several tens of feet (<1–10 m). This extra water moves ahead of the storms as a storm surge that represents an additional height of water above the normal tidal range. The wind from the storms adds further height to the storm surge, with the total height of the storm surge being determined by the length, duration, and direction of wind, plus how low the pressure gets in the center of the storm. The most destructive storm surges are those that strike low-lying communities at high tide, as the effects of the storm surge and the regular astronomical tides are cumulative.

Like many natural catastrophic events it is possible to predict the statistical probability of a storm surge of a specific height hitting a section of coastline in a specific time interval. If the height of the storm surge is plotted on a semilogarithmic plot, with the height in a linear interval and the frequency (in years) on a logarithmic scale, then a linear slope results. This means that statistically some coastal communities can plan for storm surges of certain height to occur about once in a specified interval, typically calculated as every 50, 100, 300, or 500 years, although there is no way to predict when the actual storm surges will occur. This is a long-term statistical average; one, two, three, or more 500-year events may occur over a relatively short period, but over a long time, the events average out to once every 500 years.

During some hurricanes and coastal storms the greatest destruction and largest number of deaths are associated with inundation by the storm surge. The waters can rise and cover large regions, staying high for many hours during intense storms, drowning victims in low-lying areas, and continuously pounding structures with the waves that move in on top of the storm surges.

Storm Surges and Bangladesh

The area that seems to be hit by the most frequent and most destructive storm surges is Bangladesh. A densely populated, low-lying country, Bangladesh sits mostly at or near sea level between India and Myanmar. It is a delta environment, built where the Ganges and Brahmaputra Rivers drop their sediment eroded from the Himalaya Mountains. Bangladesh is frequently flooded from high river levels, with up to 20 percent of the low-lying country being under water in any year. It also sits directly in the path of many Bay of Bengal tropical cyclones (another name for a hurricane), and has been hit by eight of the 10 most deadly hurricane disasters in world history, including Typhoon Sidr in late 2007.

On November 12 and 13, 1970, a category 3 typhoon known as the Bhola cyclone hit Bangladesh with 115-mile-per-hour (185 km/hr) winds, and a 23-foot (7-m) high storm surge that struck at the astronomically high tides of a full moon. The result was devastating, with about 500,000 human deaths and a similar number of farm animals perishing. The death toll is hard to estimate in this rural region, with estimates ranging from 300,000 to 1 million people lost in this one storm alone. Most perished from flooding associated with the storm surge that covered most of the low-lying deltaic islands on the Ganges River. The most severely hit area was in Tazmuddin Province, where nearly half the population of 167,000 in the city of Thana were killed by the storm surge. Again in 1990 another cyclone hit the same area, this time with a 20-foot (6.1-m) storm surge and 145-mile-per-hour (233.4 km/hr) winds, killing another 140,000 people and another half-million farm animals. In November 2007 Bangladesh was hit by a powerful category 5 cyclone, with 150 mph (242 km/hr) winds and was inundated with a 20-foot (6-m) high storm surge. Since the 1990 storm the area had a better warning system in place, so many more people evacuated low-lying areas before the storm. Still, it is estimated that 5,000–10,000 people perished during Typhoon Sidr, most from the effects of the storm surge.

FLASH FLOODS

Flash floods result from short periods of heavy rainfall and are common near warm oceans, along steep mountain fronts in the path of moist winds, and in areas prone to thunderstorms. They are well known from the mountain and canyon lands of the U.S. desert Southwest and many other parts of the world. Some of the heaviest rainfalls in the United States have occurred along the Balcones escarpment in Texas. Atmospheric instability in this area often forms along the boundary between dry desert air masses to the northwest and warm moist air masses rising up the escarpment from the Gulf of Mexico to the south and east. Up to 20 inches (0.5 m) of rain have fallen along the Balcones escarpment in as few as three hours from this weather situation. The Balcones escarpment also seems to trap tropical hurricane rains, such as those from Hurricane Alice, which dumped more than 40 inches (102 cm) of rain on the escarpment in 1954. The resulting floodwaters were 65 feet (20 m) deep, one of the largest floods ever recorded in Texas. Approximately 25 percent of the catastrophic flash-flooding events in the United States have occurred along the Balcones escarpment. On a slightly longer timescale tropical hurricanes, cyclones, and monsoonal rains may dump several feet of rain over periods of a few days to a few weeks, causing fast, but not quite flash, flooding.

The national record for the highest, single-day rainfall is held by the south Texas region, when Hurricane Claudette dumped 43 inches (1.1 m) of rain on the Houston area in 1979. The region was hit again by devastating floods during June 8–10, 2001, when an early-season tropical storm suddenly grew off the coast of Galveston, dumping 28–35 inches (0.7–0.9 m) of rain on Houston and surrounding regions. The floods were among the worst in Houston's history, leaving 17,000 homeless and 22 dead. More than 30,000 laboratory animals died in local hospital and research labs, and the many university and hospital research labs experienced hundreds of millions of dollars in damage. Fifty million dollars were set aside to buy out the properties of homeowners who had built on particularly hazardous floodplains. Total damages exceeded $5 billion. The standing water left behind by the floods became breeding grounds for disease-bearing mosquitoes, and the humidity led to a dramatic increase in the release of mold spores, which cause allergies in some people and are toxic to others.

The Cherrapunji region in southern India at the base of the Himalaya Mountains has received the world's highest rainfalls. Moist air masses from the Bay of Bengal move toward Cherrapunji, where they begin to rise over the high Himalayas. This produces a strong orographic effect, where the air mass cannot hold as much moisture as it rises and cools, so heavy rains result. Cherrapunji has received as many as 30 feet (9 m) of rain in a single month (July 1861) and more than 75 feet (23 m) of rain for all of 1861.

Flash floods typically occur in localized areas where mountains cause atmospheric upwelling, leading to the development of huge convective thunderstorms that can pour several inches of rain per hour onto a mountainous terrain, which focuses the water into steep-walled canyons. The result can be frightening, with floodwater thundering down canyons in steep walls that crash into and wash away all in their paths. Flash floods can severely erode the landscape in arid and sparsely vegetated regions but do much less to change the landscape.

Many canyons in mountainous regions have fairly large upriver parts of their drainage basins. Sometimes the storm that produces a flash flood with a wall of water may be located so far away that people in the canyon do not even know it is raining somewhere, or that they are in immediate grave danger. Such was the situation in some of the examples described below.

A number of factors other than the amount of rainfall determine the severity of a flash flood. The shape of the drainage basin is important, because it determines how quickly rainfall from different parts of the basin converges at specific points. The soil moisture and previous rain history are important, as are the amounts of vegetation, urbanization, and slope.

Big Thompson Canyon, Colorado, 1976

Big Thompson Canyon is a popular recreation area about 50 miles (80 km) northwest of Denver, in the Front Ranges of the Rocky Mountains. On July 31, 1976, a large thunderhead cloud had grown over the front ranges, and it suddenly produced a huge cloudburst (rainfall) instead of blowing eastward over the plains as it normally does. Approximately 7.5 inches (0.2 m) of rain fell in a four-hour period, an amount approximately equal to the average yearly rainfall in the area. The steep topography focused the water into Big Thompson Canyon, where a flash flood with a raging 20-foot (6-m) high wall of water rushed through the canyon narrows at 15 mph (24 km), killing 145 people who were driving into or out of the canyon. As the wall of water roared through the canyon, many abandoned their cars and scrambled up the canyon walls to safety, only to watch their cars wash away in the floods. Those who climbed the canyon walls to escape the flash flood survived, but others perished in the flood. In addition to the deaths, this flash flood destroyed 418 homes, wrecked 52 businesses, and washed away 400 cars. Damage totals are estimated at $36 million.

Flash Floods in the Northern Oman Mountains

The Northern Oman (Hajar) Mountains are a steep, rugged mountain range on the northeastern Arabian Peninsula, with deep, long canyons that empty into the Gulf of Oman and the Arabian Sea. These are normally dry canyons or wadis, and the local villagers dig wells in the wadi bottoms to reach the groundwater table for use in homes and agriculture. The region is normally very dry, but infrequent thunderstorms grow and explode over parts of the mountains. Occasionally a typhoon works its way from the Indian Ocean across the Arabian Peninsula and may also dump unusual amounts of rain on the mountains. In either situation the canyons become extremely unsafe, and local villagers have tales of flash floods with hundred-foot (30-m) tall walls of water wiping away entire settlements, leaving only coarse gravel in their place. The inhabitants of this region have learned to build their villages on high escarpments above the wadis, out of reach of the rare but devastating flash flood. Older destroyed villages are visible in some wadi floors, but the wisdom acquired from experiencing a devastating flash flood has encouraged these people to move to higher ground. The inconvenience of being located a hundred feet or more above their water source is avoided by building long aqueduct-like structures known as *falaj* from water sources located at similar elevations far upstream, and letting gravity bring the water to the elevated village. In August 2007 Typhoon Gonu caused severe flooding across northern Oman, with floods ripping through mountain canyons and inundating the streets of Muscat with 5–10 feet (1–3 m) of water. Damage was severe with many homes and shops destroyed, and people needed to be rescued from the desert streets by motorboats.

Flash Floods in the Southern Alps and Algeria, 2000 and 2001

In November 2001 parts of Algeria in North Africa received heavy rainfall over a period of two days that led to the worst flooding and mudslides in the capital city, Algiers, in more than 40 years. An estimated 1,000 died in Algiers, being buried by fast-moving mudflows that swept out of the Atlas Mountains to the south and moved through the city, hitting some of the poorest neighborhoods with the worst flooding. The Bab El Oued District, one of the poorest in Algiers, was hit the worst, where 600 people were buried under mud flows several feet (1 m) thick.

These floods followed similar heavy rains and mudslides that devastated parts of southern Europe in October 2000. Northern Italy and Switzerland were among the worst hit, where water levels reached their highest in 30 years, killing about 50 people. In Switzerland the southern mountain village of Gondo was devastated when a 120-foot (37-m) wide mudflow ripped through the town center, removing 10 homes (one-third of the village) and killing 13 people. Numerous roads, bridges, and railroads were washed away throughout the region, stretching from southern France, through Switzerland and Italy, to the Adriatic Sea. Crops were destroyed on a massive scale. Tens of thousands of people had to be evacuated from the region, and total damage estimates are in the range of many billions of dollars.

REGIONAL FLOOD DISASTERS

Some flooding events are massive, covering with water hundreds of thousands of acres along the entire floodplain of a river system. These floods tend to rise slowly and may have high water for weeks or even months. History has shown that many levees fail during regional long-term flooding events, because most levees are designed to hold back high water for only a short time. The longer the water remains high, the more the water pressure acts on the levee, slowly forcing the water into the pores, letting the water seep into and under it. This often causes levee failure and explains why so many levees fail in long-term regional floods. Long-term flooding events can affect hundreds of thousands or millions of people, and cause widespread disease, famine, loss of jobs, and displacement of populations as a result of the disaster. Floods of this magnitude are among the costliest of all natural disasters.

Mississippi River Basin and the Midwest of the United States

The Mississippi River is the largest river basin in the United States, and the third-largest river basin in the world. It is the site of frequent, sometimes devastating floods. All of the 11 major tributaries of the Mississippi have also experienced major floods, including events that have at least quadrupled the normal river discharge in 1993, 1973, 1927, 1909, 1903, 1892, and 1883. Three of the major rivers (Mississippi, Missouri, and Illinois) meet in St. Louis,

Satellite image of the St. Louis, Missouri, area that shows the Mississippi, Missouri, and Illinois Rivers at normal flow stages *(Image taken August 14, 1991; NASA images created by Jesse Allen, Earth Observatory, using data provided courtesy of Landsat Project Science Office)*

which has seen some of the worst flooding along the entire system.

Floods along the Mississippi in the 1700s and 1800s prompted the formation of the Mississippi River Commission, which oversaw the construction of high levees along much of the length of the river from New Orleans to Iowa. By 1926 more than 1,800 miles (2,896.8 km) of levees had been constructed, many of them higher than 20 feet (6.1 m). The levees imparted a false sense of security against the floodwaters of the mighty Mississippi, and they restricted the channel, causing floods to rise more quickly and forcing the water to flow faster.

Many weeks of rain in late fall 1926 followed by high winter snowmelts in the upper Mississippi River basin caused the river to rise to alarming heights by spring 1927. Worried residents all along the Mississippi strengthened and heightened the levees and dikes along the river, hoping to avert disaster. The crest of water was moving through the upper Midwest and had reached central Mississippi, and the rains continued. In April levees began collapsing along the river, sending torrents of water over thousands of acres of farmland, destroying homes, killing livestock, and leaving 50,000 people homeless. One of the worst-hit areas was Washington County, Mississippi, where an intense late April storm dumped an incredible 15 inches (457.2 cm) of rain in 18 hours, causing additional levees along the river to collapse. One of the most notable was the collapse of the Mounds Landing levee, which caused a 10-foot-deep lobe of water to cover the Washington County town of Greenville on April 22. The river reached 50 miles in width and had flooded approximately 1 million acres, washing away an estimated 2,200 buildings in Washington County alone. Many perished trying to keep the levees from collapsing and were washed away in the deluge. The floodwaters remained high for more than two months, and people were forced to leave the area (if they could afford to) or to live in refugee camps on the levees, which were crowded and unsanitary. An estimated 1,000 people perished in the floods of 1927, some from the initial deluge, more from famine and disease in the months following the initial inundation by the floodwaters. More than 1 million people were displaced from their homes, and a total of 27,000 square miles (43,450 km^2, or 16.6 million acres) were flooded. Crop losses amounted to $102.6 million, and 162,000 homes were inundated.

Another wet year along the Mississippi was 1972, with most tributaries and reservoirs filling by the end of summer. The rains continued through winter 1972–73, and the snowpack thickened over the northern part of the Mississippi basin. The combined snowmelts and continued rains caused the river to reach flood levels at St. Louis in early March, before the snow had even finished melting. Heavy rain continued throughout the Mississippi basin, and the

Satellite image of the St. Louis, Missouri, area that shows the Mississippi, Missouri, and Illinois Rivers at stages at the height of the 1993 flood *(Image taken August 19, 1993; NASA images created by Jesse Allen, Earth Observatory, using data provided courtesy of Landsat Project Science Office)*

The Blackfoot River in Montana, showing natural meanders, oxbow lakes, and floodplain *(James Steinberg/ Photo Researchers, Inc.)*

river continued to rise through April and May, spilling into fields and low-lying areas. The Mississippi was so high that it rose to more than 50 feet above its average levels for much of the lower river basin, and these heights caused many of the smaller tributaries to back up until they too reached this height. The floodwaters rose to levels not seen for 200 years. At Baton Rouge, Louisiana, the river nearly broke through its banks and established a new course to the Gulf of Mexico, which would have left New Orleans without a river.

The floodwaters began peaking in late April, causing 30,000 to be evacuated in St. Louis by April 28, and close to 70,000 in the region. The river remained at record heights throughout the lower drainage basin through late June. Damage estimates exceeded $750 million (1973 dollars).

In late summer 1993 the Mississippi and its tributaries in the upper basin rose to levels not seen in more than 130 years. The discharge at St. Louis was measured at more than 1 million cubic feet (28,320 m^3) per second. The weather situation that led to these floods was remarkably similar to that of the floods of 1927 and 1973, only worse. High winter snowmelts were followed by heavy summer rainfalls caused by a low-pressure trough that stalled over the Midwest, because it was blocked by a stationary high-pressure ridge that formed over the East Coast of the United States. The low-pressure system drew moist air from the Gulf of Mexico that met the cold air from the eastern high-pressure ridge, initiating heavy rains for much of the summer. The rivers continued to rise until August, when they reached unprecedented flood heights. The discharge of the Mississippi was the highest recorded, and the height of the water was even greater because all the levees that had been built restricted the water from spreading laterally and caused it to rise more rapidly than it would have without the levees in place. More than two-thirds of all the levees in the upper Mississippi River basin were breached, overtopped, or damaged by the floods of 1993. Forty-eight people died in the 1993 floods, and 50,000 homes were damaged or destroyed. Total damage costs are estimated at more than $20 billion.

The examples of the floods of 1927 and 1993 on the Mississippi reveal the dangers of building extensive levee systems along rivers. Levees adversely affect the natural processes of the river and may actually make floods worse. Their first effect is to confine the river to a narrow channel, causing the water to rise faster than if it were able to spread across its floodplain. Additionally, since the water can no longer flow across the floodplain, it cannot seep into the ground as effectively, and a large amount of water that the ground would normally absorb must now flow through the confined river channel. The floods are therefore larger because of the levees. A third hazard of levees is associated with their failure. When a levee breaks, it does so with the force of hundreds or thousands of acres of elevated river water pushing it from behind. The force of the water that broke through the Mounds Landing Levee in the 1927 flood is estimated to be equivalent to the force of water flowing over Niagara Falls. If the levees were not in place, the water would have risen gradually and would have been much less catastrophic when it eventually entered the farmlands and towns along the Mississippi River basin.

The U.S. Army Corps of Engineers is mitigating another hazard and potential disaster where the Atchafalaya branches off the Mississippi. Over geological time the Mississippi River has altered its course so that its mouth has migrated east and west by hundreds of miles. Each course of the river has produced its own delta, which subsides below sea level after the river migrates to another location. Subsidence of the delta deposit occurs primarily because the river no longer replenishes the top of the delta, and the buried muds gradually compact as the weight of the overlying sediments expels water from the pore spaces. As the delta subsides to sea level, waves add to the erosion, keeping the delta surface below sea level. At the present time the lower Mississippi River follows a long, circuitous course from where the Atchafalaya branches off from it, past New Orleans, to its mouth near Venice. The Mississippi is ready to switch its course back to its earlier position, following the Atchafalaya, which would offer it a shorter course to the sea, and would take less energy to transport sediment to the Gulf of Mexico. If this were to occur, it would be devastating to the lower delta, which would quickly subside below sea level. The city of New Orleans is currently below sea level and protected from the river, storms, and the Gulf of Mexico only by high levees built around the city. To prevent this disaster the Army Corps has constructed an extensive system of diversions, levees, and dams at the Mississippi/Atchafalaya junction to keep the Mississippi in its channel.

Yellow River, China

More people have been killed from floods along the Yellow River in China than from any other natural feature, whether river, volcano, fault, or coastline. An estimate of millions of people have died as a result of floods and famine generated by the Yellow River, which has earned it the nickname River of Sorrow in China.

The Yellow River flows out of the Kunlun Mountains across much of China into the wide lowland basin between Beijing and Shanghai. The river has switched courses in its lower reaches at least 10 times in the last 2,500 years. It currently flows into Chihli (Bohai) Bay, then into the Yellow Sea.

The Chinese have attempted to control and modify the course of the Yellow River since dredging operations in 2356 B.C.E. and the construction of levees in 602 B.C.E. One of the worst modern floods along the Yellow River occurred in 1887, when the river rose over the top of the 75-foot (22-meter) high levees and covered the lowlands with water. More than 1 million people died from the floods and subsequent famine. Crops and livestock were destroyed, and sorrow returned to the river.

The Yellow River was also the site of a mixed natural and unnatural disaster in 1938. As part of the war effort, in 1938 Chiang Kai-shek (Jiang Jieshi, Nationalist Chinese leader and later, president of Taiwan) is said to have attacked and bombed the levees along the Yellow River to trap the advancing Japanese army. The Japanese had been brutally advancing inland from the coast, and the Chinese adopted a scorched earth policy, burning towns and villages before retreating to leave nothing for the Japanese. The war was causing more than a thousand deaths a day for the Japanese, and more for the Chinese, in some of history's largest military battles. When the Japanese army arrived in Suchow (now Xuzhou, Jiangsu Province), the area was deserted. They captured the empty city on May 20, 1938, and the Japanese were preparing to move farther inland. But torrential rains were causing flooding along the Yellow and Yangtze Rivers, and progress was slow. Then, in June, the levees along the Yellow River were apparently cut (some historians say they broke naturally), and one of the river's greatest floods ensued. The river escaped, initially inundating 500 square miles (1,295 km^2), and took another 1 million lives as the flooding spread throughout June and July while rains continued. Despite the enormous loss of life and destruction, the massive floods of the Yellow River, and the Yangtze, the Japanese began a disorganized retreat in rafts and boats. They next tried to advance up the Yangtze, and with great loss of life made progress and captured towns up to Kiukang (now Jiujiang, in Jiangxi Province). On August 3 the Chinese army cut the dikes on the Yangtze, flooding and killing many more people, but effectively ending the two-month-long drive by the Japanese army up the Yangtze. By the middle of August the Japanese were retreating from their drive into central China up the Yangtze, following the floodwaters to the sea.

The Yellow River is continuing its natural process of building up its bottom, and the people along the river continue to raise the level of the levees to keep the river's floods out of their fields. Today, the river bottom rests an astounding 65 feet (20 meters) above the surrounding floodplain, a testament to the attempts of the river to find a new, lower channel and to abandon its current channel in the process of avulsion. What will happen if heavy rains cause another serious flood along the River of Sorrow? Will another million people perish?

URBANIZATION AND FLASH FLOODING

Urbanization is the process of building up and populating a natural habitat or environment, such that the habitat or environment no longer responds to input the way it did before being altered by humans. When heavy rains fall in an unaltered natural environment, the land surface responds to accommodate the additional water. Desert regions may experience severe erosion in response to the force of falling raindrops that dislodge soil and also by overland flow during heavy rains. This causes upland channel areas to enlarge to accommodate larger floods. Areas that frequently receive heavy rains may develop lush vegetative cover, which helps to break the force of the raindrops and reduce soil erosion, and the extensive root system holds the soil in place against erosion by overland flow. Stream channels may be large so that they can accommodate large-volume floods.

When the natural system is altered in urban areas, the result can be dangerous. Many municipalities have paved over large parts of drainage basins and covered much of the recharge area with roads, buildings, parking lots, and other structures. The result is that much of the water that used to seep into the ground and infiltrate into the groundwater system now flows overland into stream channels, which may themselves be modified or even paved over. The net effect of these alterations is that flash floods may occur much more frequently than in a natural system, since more water flows into the stream system than before the alterations. The floods may occur with significantly lower amounts of rainfall as well, and since the water flows overland without slowly seeping into the ground, the flash floods may reach urban areas more quickly than the floods did before the alterations to the stream system. Overall the effect of urbanization is faster, stronger, bigger floods that have greater erosive power and do more damage. It is almost as if the natural environment responds to urban growth by increasing its ability to return the environment to its natural state.

Urbanization and Changes in the Missouri River Floodplain

The Missouri River stretches more than 2,300 miles and drains one-sixth of the United States. It was once one of the wildest stretches of rivers in the American Midwest. During the past two centuries the Missouri, along with its adjacent wetlands and floodplains, has been dramatically modified in various attempts to promote transportation, agriculture, and development. These modifications have included draining wetlands for cultivation, straightening stream channels to facilitate navigation, stabilizing banks to prevent erosion, and constructing agricultural levees, dams, reservoirs, and flood-control levees to control water flow and exclude floodwaters from the floodplain. These modifications have resulted in a severe loss of wetlands.

Historically the Missouri River floodplain below Sioux City, Iowa, covered 1.9 million acres. According to the Sierra Club, modifications in the river-floodplain system described above have resulted in the loss of approximately 168,000 acres of natural channel, 354,000 acres of meander belt habitat, and 50 percent of the river's surface. In addition, shallow-water habitat has been reduced by up to 90 percent in some areas, while sandbars, islands, oxbows, and backwaters have been virtually eliminated. Forested floodplains along the Missouri have decreased from 76 percent in the 19th century to 13 percent in 1972, and cultivated lands have increased from 18 to 83 percent.

By the late 1970s the lower Missouri River had been totally channelized and its natural floodplain ecosystems almost completely converted to agricultural or other uses. Today levees and other flood-control structures flank the lower Missouri River for most of its length. Environmental groups such as the Sierra Club, Great Rivers Habitat Alliance, and Ducks Unlimited have been fighting further development of the floodplain to prevent the complete loss of this habitat and reduce the risks of hazardous floods along the system.

SUMMARY

Floods are the costliest, deadliest, most common natural disaster to affect humans. Individual floods have killed on the order of a million people at a time, and other floods cause billions of dollars in damages and ruin entire towns, disrupt livelihoods of hundreds of thousands of people, and bring disease and famine to affected regions.

There are many types of floods, ranging from isolated flash floods that sweep down isolated mountain canyons, to coastal floods associated with tropical cyclones and other large ocean storms. Bangladesh has experienced the most frequent and most deadly storm surge–related flooding of anywhere in the world, with some storms killing hundreds of thousands of people. Some of the most devastating floods in history have been large, slowly rising floods that cover entire regions, with the Yellow and Yangtze Rivers of China having the dubious distinction of recording the two deadliest floods of all time, each flood claiming more than 1 million lives. Floods along the Mississippi-Missouri-Ohio River basins in the United States have been frequent and long-lasting, and have caused great damage to areas on the floodplains that have been built up for commercial or residential uses. Had these areas remained natural or been used for agriculture, the damage would have been much less, and the river floods would have been lower in magnitude. Levees along these rivers have constricted the rivers with time, raising their base and in turn raising the river flood stages, leading to more disastrous floods.

People have modified rivers and floodplains for navigation and flood control for thousands of years, often with disastrous results. In the United States construction of levees along the Mississippi River began essentially as soon as western settlers arrived in the New Orleans area. Time and again levees were built, floods seemed to become larger, and the levees were breached or collapsed through processes of underseepage, piping, scouring, or liquefaction. Some scientists noticed that as the levees were built higher, the base of the river seemed to aggrade or rise as well. However, it took 250 years before quantitative evidence demonstrated that the construction of levees and other flood-control measures constricted the river and caused flood stages to rise higher and faster, and become more dangerous, with increasing constriction of the river by levees. This understanding has not reached the level of policy in the United States, as rivers are still being actively constricted by levees, and floodplains are being widely developed.

Urbanization of floodplains also causes floods to rise faster, be more powerful, and do more damage than in natural settings. Some places such as the American Southwest and parts of the Middle East have extensively altered the natural drainage network to provide drinking and irrigation water in arid and semiarid climates. These water resources are presently extremely stressed and reaching their limits, yet the population keeps on expanding at alarming rates. New sources of water must be sought to meet the demands of a growing global population.

See also DESERTS; DRAINAGE BASIN (DRAINAGE SYSTEM); FLUVIAL; GEOLOGICAL HAZARDS; GEOMORPHOLOGY; GROUNDWATER.

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fluvial Rivers are the main geological instruments that shape the surface of the land, carrying pieces of the continents grain by grain, steadily to the sea. The term *fluvial* refers to deposits and landforms created by the action of flowing rivers and streams, and also the processes that occur in these rivers and streams. Fluvial systems slowly erode mountains and fill deep valleys with alluvium, and serve as passageways for people, aquatic fauna and flora, sediment, and dissolved elements from one place to another. River systems are not simply channels, but are intricately linked to associated floodplains and deltas, and they are affected by processes that occur throughout the entire drainage basin. Rivers transport water in a critical step in the hydrological cycle, and bring freshwater to even the driest places on Earth. Nearly every city and town in the world is built with a river flowing through it or near it, so vital is water for drinking, agriculture, and navigation. Rivers have controlled history, bringing life to some areas, but they are also prone to floods, sometimes bringing disaster from the same source that has fed populations for ages.

GEOMETRY OF FLUVIAL SYSTEMS

Fluvial systems including streams and rivers are dynamic, ever-changing systems that represent a balance between driving and resisting forces. The ability of a stream to erode and transport sediments depends on how much energy is in the water as it flows, versus how much is consumed by the resistance to flow. As the velocity of the water in the stream increases, the resistance to flow provided by the stream banks, boulders, and material carried by the stream also increases. Therefore at any point in the stream the velocity of the water and the shape of the stream channel represent a balance between the energy causing the flow of water and the energy consumed by resistance to flow.

The water in the stream channel may exhibit one of two main types of flow, laminar or turbulent. In a laminar flow pattern the paths of water particles are parallel and smooth, and the flow is not very erosive. Resistance to flow in laminar systems is provided by internal friction between individual water molecules, and the resistance is proportional to flow velocity. The frictional resistance in laminar flow systems increases from the top of the water surface to the base of the streambed. In contrast, in turbulent flow the direction of flow and the velocity vary in all directions within the stream, and water is being continuously exchanged between adjacent flow zones. In turbulent flows the water may move in different directions and often forms zones of sideways or short backward flows called eddies. These significantly increase the resistance to flow. In turbulent flows the resistance is proportional to the square of the flow velocity. Many zones of turbulence and turbulent eddies are generated along channel margins where the water velocity is reduced by frictional resistance from the bed material and riverbanks.

Streams are defined primarily by their channels, which are the elongate depressions where the water flows. Several different types of stream banks separate the stream channels from the adjacent flat floodplains, including low-profile point bars, steep-cut banks, and eroded cliffs. The shape of the channel and its pattern in map view represents the balance between the driving and resisting forces in the different conditions or environments through which the stream passes. Streams create their broad, flat floodplains by erosion and redeposition during floods, and these plains serve as the stream bottom during large floods. Even though floodplains may have no water over them for many tens of years, they are part of the stream system and the stream will return. Many communities in the United States and elsewhere have built extensively on the floodplains, and these communities will eventually be flooded.

Stream channels are self-adjusting features—they modify their shapes and sizes to best accommodate the amount of water flowing in the stream. A stream's discharge is a measure of the amount of water passing a given point per unit time. During floods the discharge may be two, three, ten, or more times normal levels. The stream channel may then overflow, causing the water to spread across the adjacent floodplain, inundating towns and farms. The cross-sectional shape of streams changes with time and amount of water flow through the channel. The shape of a stream channel is also different in the upstream and downstream parts of the system, as the slope and volume of water changes along the course of the river. Small, narrow streams are typically as deep as they are wide, whereas large streams and rivers are much wider than they are deep.

The gradient or slope of a stream is a measure of the vertical drop over a given horizontal distance, and the average gradient decreases downstream. Going downstream, several changes also occur. First, the discharge increases, which in turn causes both the width and the depth of the channel to increase. Yet downstream, as the gradient decreases, the velocity increases. Although one might expect the velocity of a stream to decrease with a decrease in slope (gradient), anyone who has seen the Mississippi at New Orleans or the Nile at Cairo can testify to their great velocity as compared to their upstream sources. Two reasons explain this increase in velocity. First, the upstream portions of these mighty rivers have courses with many obstacles and more friction per stream volume, reducing velocity. Second, more water flows in the downstream portions of the streams, and this has to move quickly to allow the added discharge from the various tributaries that merge with the main stream.

The base level of a stream is the limiting level below which a stream cannot erode the land. The ultimate base level is sea level, but in many cases streams entering a lake or dammed region form a local base level.

EROSION, SEDIMENT TRANSPORT, AND DEPOSITION IN FLUVIAL SYSTEMS

Most energy in streams is dissipated by turbulent flow, but a small part of a stream's energy is used to erode and transport sediments downstream. Streams carry a variety of materials as they make their way to the sea, and the way this material is eroded and transported depends on the energy balance in the stream. These materials range from minute dissolved particles and pollutants to giant boulders moved only during the most massive floods. The bed load consists of the coarse particles that move along or close to the bottom of the streambed. Particles move more slowly than the stream by rolling, bouncing, or sliding. Saltation is the movement of a particle by short, intermittent jumps caused by the current lifting the particles. Bed load typically constitutes 5–50 percent of the total load carried by the stream, with a greater proportion carried during high-discharge floods. The suspended load consists of the fine particles suspended in the stream. This makes many streams muddy, and the suspended load consists of silt and clay that moves at the same velocity or slightly lower than the stream. The suspended load generally accounts for 50–90 percent of the total load carried by the stream. The dissolved load of a stream consists of dissolved chemicals, such as bicarbonate, calcium, sulfate, chloride, sodium, magnesium, and potassium. The dissolved load tends to be high in streams fed by groundwater. Pollutants, such as fertilizers and pesticides from agriculture, and industrial chemicals also tend to be carried as dissolved load in streams.

Most of the larger particles in streambeds are usually not moving, but move only for short distances at times of high-flow velocity and discharge of the stream. The picking up of particles from the bed load of a stream and the erosion of material from the banks is known as entrainment, a process that depends on the erosive power of the flow and the resistance of the particles. There is a wide range in the sizes and amounts of material that can be entrained and transported by a stream. The competence of a stream refers to the maximum size of particles that can be entrained and transported by a stream under a given set of hydraulic conditions, measured in diameter of the largest bed load. A stream's capacity is the potential load it can carry, measured in the amount (volume) of sediment passing a given point in a set amount of time. The amount of material carried by streams depends on a number of factors. Climate studies show erosion rates are greatest in climates between a true desert and grasslands. Topography affects stream load as rugged topography contributes more detritus, and some rocks are more erodable. Human activity, such as farming, deforestation, and urbanization, all strongly affect erosion rates and stream transport. Deforestation and farming greatly increase erosion rates and supply more sediment to streams, increasing their loads. Urbanization has complex effects, including deceased infiltration and decreased times between rainfall events and floods, as discussed in detail below.

Erosion and Deposition along Stream Banks

The process of entrainment determines how a stream erodes its bank and bed, and the type of sedimentary load the stream can carry. The lateral, or sideways, erosion of a stream bank is an important process that strongly influences other stream processes. The erosion of the stream banks is accomplished through a combination of events, including weathering of the material on the stream bank, mass wasting that may cause the bank to collapse into the stream, and the actual entrainment of the sedimentary particles into the bed load of the stream.

The weathering of the bank material, typically loose sediment deposited by the stream, makes it weaker and more susceptible to mass movement and collapse into the river. The amount of moisture in the soil on the banks is important in this stage, as increased moisture, such as during rain or flooding events, decreases the frictional resistance between the bank sediments, and that is partly why many banks collapse during rains and flooding events. In areas prone to freeze-thaw cycles, stream banks are also susceptible to collapse from the action of frost wedging in small cracks, pushing blocks of sediment into the river. Many stream banks have layers of sand, gravel, and mud deposited on floodplains during earlier stages of the stream development. In these cases groundwater may move along the gravel and sand layers, seeping out along the river bank. This movement of groundwater can actually carry sediment away from the bank into the stream in a process called sapping. This groundwater sapping creates overhanging banks along the river, which are then prone to collapse. The water along these layers may also reduce the friction on this layer, creating a plane along which overlying layers often slide into the river along, forming planar slides. Planar slides are recognized as important mass wasting processes along many riverbanks, including the Mississippi River.

River and stream banks collapse with many different styles of mass wasting, including slipping of large sections of the bank on rotational slides, slumps into the river, and wholesale collapse of large slabs, especially where the stream has undercut the riverbank. Many factors determine which kind of collapse occurs, including the layering in the riverbank/floodplain sediment, the pore fluid pressure.

After the bank materials collapse into the river, the current begins to entrain the finer-grained particles, and to move the coarser material as bed load. This carries the material away and prepares the bank for the next failure, in the steady process of the river migrating across the floodplain.

After the sediments are carried away by the river current, at some point they are deposited again. Fine particles may be carried in suspension all the way to the ocean or local reservoir, whereas most of the coarser particles move by bouncing or rolling along the stream bed. Where these sediments get deposited next depends on the interactions of the type of current in the river and the size, shape, and density of the sedimentary particles. The river channel is a dynamic environment, and the flow velocity and style, whether laminar or turbulent, can vary significantly over short distances. These local variations often determine where a sedimentary particle will be deposited, and whether the current is scouring one place or filling in another. Typically as the river is eroding a bank or scouring its base in one location, moving the material from that location downstream, the current is simultaneously depositing other sedimentary material nearby that was carried from further upstream. For instance, along one bend of a river the outer or cut bank may be eroding, whereas the inner bank of the bend may be experiencing deposition. In this way the river effectively moves its location, filling in the old channel as it cuts a new one step by step. River floodplains are naturally dynamic environments, where the natural forces in the river keep a balance by maintaining this lateral, back-and-forth type of movement of the channel as the river transports the bed and suspended load downstream.

If the river cannot move laterally, such as if confined by bedrock or by levees, it must respond by changing the level of its base. Rivers may downcut through alluvium or bedrock in response to tectonic uplift, or may rise through depositing sediments along their beds in a process called aggradation. If the river is transporting a large bed load, it naturally responds to this by moving it downstream and moving sideways. When the bank is confined, it can move only upward and deposits these extra bed load sediments along its base, causing unnatural aggradation.

CHANNEL PATTERNS

River channels represent a quasi-equilibrium condition between the river discharge, flow regime (whether laminar or turbulent), amount of sediment being transported, and slope of the river channel. The river can respond to these variables by finding an equilibrium or quasi-equilibrium condition by adjusting the channel shape (width and depth), the velocity of the flow, the roughness of the bed and bank, and the slope of the bed. The slope of a riverbed can be adjusted by the river by increasing or decreasing the number of its bends, or meanders. If the river needs to lower the slope to maintain a quasi-equilibrium condition, then it can increase the number of bends and flow more parallel to the contours. If the river needs to increase the slope, it can cut through the banks and flow straight downhill, attaining a slope equal to the regional gradient. This is one of the reasons rivers have so many different forms, from straight to wildly meandering channels.

Straight Channels

Stream channels are rarely straight, and a stream is said to have a straight channel if the ratio of the stream length to valley length is 1.5. Although this ratio, called the sinuosity, seems to have no particular mechanical significance, this measure is useful to describe the shape of stream channels. Many stream channels are straight because they inherit their path from incision into an underlying bedrock fracture, whereas others are relatively straight for short distances. In either case the velocity of flow changes in different places and, internally, the water in the channel naturally starts to develop some complex flow patterns. Friction makes the flow slower on the bottom and sides of the channel, and the water develops curving traces of highest velocity in plain view, and also begins to circulate in loops from the surface, to the streambed, and back to the surface as the water moves downstream. The changing currents cause sand bars to be deposited alternately on either sides of the straight channel and for deep pools to develop between the bars. These internal bends in the river make the zone of fastest flow swing from side to side.

Straight channels are very rare, and those that do occur have many properties of curving streams. The thalweg is a line connecting the deepest parts of the channel. In straight segments the thalweg typically meanders from side to side of the stream. In places where the thalweg is on one side of the channel, a bar may form on the other side. A bar (for example, a sandbar) is a deposit of alluvium in a stream.

Meandering Streams

Most streams move through a series of bends known as meanders. The main components of meandering channels are similar to the straight channels, with greater curvature. The outer bends of meanders are typically marked by steep-cut banks, with active slumping and mass wasting into the channel, whereas the inner bends of the meanders are marked by deposition of sand and gravel. Meanders are always migrating across the floodplain by the process of the deposition of the point bar deposits and the erosion of the bank on the opposite side of the stream with the fastest flow. The thalweg, the line of fastest flow, bounces into the outer cut bank, and some of the flow moves down along this steep wall, then more slowly upward along the slope of the point bar as the water moves downstream. This results in a twisting helical flow of water in the stream channel, and keeps the outer banks erosive, with the fastest currents, and the inner point bars have slower velocity currents, and receive deposits of sand and gravel. Meanders typically migrate back and forth, and also down-valley at a slow rate. If the downstream portion of a meander encounters a slowly erodable rock, the upstream part may catch up and cut off the meander. This forms an oxbow lake, an elongate and curved lake formed from the former stream channel.

Studies on the mechanics of stream flow have revealed quantitative relationships between the wavelength of a meander (the distance from one cut bank to the next one of similar curvature), the discharge of the stream, the radius of curvature, and other stream parameters. By changing any of these variables the current in the stream will change to attempt to restore the system to an equilibrium state. Therefore it is clear that streams need to be able to maintain their migrating meandering pattern across floodplains to be in equilibrium. Any unnatural changes, such as straightening channels, narrowing channels, and the like, will naturally be met by the river with changes in other parameters that may be unexpected and potentially hazardous.

Braided Stream Channels

Braided streams consist of two or more adjacent but interconnected channels separated by bars or islands, commonly known as braid bars. Braided streams have constantly shifting channels, which move as the bars are eroded and redeposited during large fluctuations in discharge. Most braided streams have highly variable discharge in different seasons, and they carry more load than meandering streams.

Braided streams tend to be wider and shallower, and have steeper gradients than streams with undivided channels. Several factors seem to play significant roles in determining whether a stream channel becomes braided. First, the backs of the stream must be easily erodible, letting the channels migrate and contributing bedload to the channel. Second, the load must be large, as all braided streams carry high-sediment loads. Third, braided streams are characterized by rapid changes in discharge. Braided streams are common in areas such as on glacial outwash plains, where the fluctuation in discharge is large, there is abundant sediment supply, and the river banks are easily erodible.

DYNAMICS OF STREAM FLOW

Streams are dynamic systems and constantly change their channel patterns and the amount of water (discharge) and sediment being transported in the system. Streams may transport orders of magnitude more water and sediment in times of spring floods, as compared with low-flow times of winter or drought. Since streams are dynamic systems, as the amount of water flowing through the channel changes, the channel responds by changing its size and shape to accommodate the extra flow. For instance, in a gradually changing climate scenario, the discharge and load of a river may gradually change, and the river may be able to make small changes accordingly to account for these variables. At some point, however, the balance of controlling forces in the river may exceed a critical threshold value, and the channel may suddenly make a dramatic change into a completely different configuration. In another scenario a river may gradually downcut its gradient through a mountain range, starting as a juvenile high-gradient stream, and over the course of many years gradually decrease its gradient (slope) as the bed is eroded. At different stages in this evolution, the stream may make transitions, perhaps rapidly, through different channel types and flow regimes. The following five factors control how a stream behaves:

- width and depth of channel, measured in feet (meters)
- gradient, measured as change in elevation in feet per mile (m/km)
- average velocity, measured in feet per second (m/sec)
- discharge, measured in cubic feet per second (m^3/s)
- load, measured as tons per cubic yard (metric tons/m^3)

All of these factors are continually interplaying to determine how a stream system behaves. As one factor, such as discharge changes, so do the others, expressed as

$$Q = w \times d \times v$$

where Q represents discharge, w represents width, d represents depth, and v represents velocity. Other factors may also play a role, though are less important. These include the mean annual flood, meander wavelength, width-depth ratio, and sinuosity. These secondary variables are not totally independent; for instance, sinuosity and gradient are related, the mean annual flood and discharge are related, and so on. The main point is that the variables are all interrelated, and changing one can lead to changes in the others.

All factors vary across the stream, so they are expressed as averages. If one term changes, then all or one of the others must change too. For example, with increased discharge, the stream erodes, widens, and deepens its channel. With increased discharge, the stream may also respond by increasing its sinuosity through the development of meanders, effectively creating more space for the water to flow in and occupy by adding length to the stream. The meanders may develop quickly during floods because the increased stream velocity adds more energy to the stream system, and this can rapidly erode the cut banks, enhancing the meanders.

The amount of sediment load available to the stream is also independent of the stream's discharge, so different types of stream channels develop in response to different amounts of sediment load availability. If the sediment load is low, streams tend to have simple channels, whereas braided stream channels develop where the sediment load is greater. If a large amount of sediment is dumped into a stream, the stream will respond by straightening, thus increasing the gradient and stream velocity, and increasing the stream's ability to remove the added sediment.

When streams enter lakes or reservoirs along their path to the sea, the velocity of the stream suddenly decreases. This causes the sediment load of the stream or river to be dropped as a delta on the lake bottom, and the stream attempts in this way to fill the entire lake with sediment. The stream is effectively attempting to regain its gradient by filling the lake, then eroding the dam or ridge that created the lake in the first place. When the water of the stream flows over the dam, it does so without its sediment load and therefore has greater erosive power and can erode the dam more effectively.

The concept of a graded stream is widely used by geomorphologists to describe how a river may adjust its environment to transport its sedimentary load with the least energy required. In this concept the stream gradually (over many years) erodes its bed to attain an equilibrium gradient just right for transporting the sedimentary load when balanced with the types of channels characteristics and velocity available in the area. This graded profile is typically concave up, steeper in the headwaters, and with a low slope near the mouth of the river. Graded streams are thought to be in a state of relative equilibrium; changes in one variable will be accommodated by changes in the other to keep the balance of forces.

FLUVIAL DEPOSITIONAL FEATURES: FLOODPLAINS, TERRACES, AND DELTAS

During great floods, streams flow way out of their banks and fill the adjacent floodplain. During these times, when the water flows out of the channel, its velocity suddenly decreases and it drops its load, forming levees and overbank silt deposits on the floodplain.

Floodplains

Floodplains are relatively flat areas that occupy valley bottoms, and generally comprise unconsolidated sediments. Most of these sediments are deposited by the river, but some may come from other processes, such as from slopes along the margins of the valley and even from wind or Aeolian processes. In natural river systems (ones not disturbed by levees, etc.) the river will periodically rise out of its banks and cover the floodplain with water and fine sediments. Different flood levels and different parts of the floodplain may be reached with different frequencies of floods. In most natural rivers in humid climates the river rises out of the banks every year or two. Higher levels of the floodplain may be reached only during higher floods, such as *the 100-year flood,* a term that describes the height of water statistically expected to be reached only once every hundred years.

Floodplains are an essential part of the river system, as they allow the river to adjust to changing conditions. During floods the floodplains hold water, reducing the speed and height of floods in downstream areas, and the unconsolidated sediments in the floodplain also absorb large quantities of the water, reducing the amount that flows downstream. The floodplain also serves as a large temporary and mobile storage area for the sediments that have been eroded from throughout the watershed. This storage is important for maintaining the river's ability to respond to changes in discharge, climate, and other variables, so it needs to remain in contact with the river. Attempts to isolate the floodplain from the river by construction of levees and artificial canals disrupt the natural flow and separate different components of the system, setting the stage for disasters.

Stream Terraces

Terraces are abandoned floodplains formed when a stream flowed above its present channel and floodplain level. These form when a stream erodes downward through its deposits, to a new lower level. Paired terraces are terrace remnants that lie at the same elevation on either side of the present floodplain. Nonpaired terraces form at different levels on either side of the current floodplain, and imply several episodes of erosion. Rivers and streams may downcut through older terraces for a variety of reasons, including climatically influenced changes in discharge, or uplift of the river valley and slopes, causing a change in the river profile.

Deltas

When a stream enters the relatively still water of a lake or the ocean, its velocity and capacity to hold sediment drop suddenly. Thus the stream dumps its sediment load here, and the resulting deposit is known as a delta. Where a coarse sediment load of an alluvial fan dumps its load in a delta, the deposit is known as a fan-delta. Braid-deltas are formed when braided streams meet local base level and deposit their coarse-grained load. When a stream deposits its load in a delta, it first drops the coarsest material, then progressively finer material farther out, forming a distinctive sedimentary deposit. The resulting foreset layer is thus graded from coarse nearshore to fine offshore. The bottomset layer consists of the finest material, deposited far out. As this material continues to build outward, the stream must extend its length and forms new deposits, known as topset layers, on top of all this. Most of the world's large rivers—the

Mississippi, Nile, and Ganges—have built huge deltas at their mouths, yet all of these differ in detail.

DRAINAGE SYSTEMS

A drainage basin is the total area that contributes water to a stream, and the line that divides different drainage basins is known as a divide (such as the continental divide) or interfluve. Drainage basins are the primary landscape units or systems concerned with the collection and movement of water and sediment into streams and river channels. Drainage basins consist of a number of interrelated systems that work together to control the distribution and flow of water within the basin. Hillslope processes, bedrock and surficial geology, vegetation, climate, and many other systems all interact in complex ways that determine where streams will form and how much water and sediment they will transport. A drainage basin's hydrologic dynamics can be analyzed by considering these systems along with how much water enters the basin through precipitation and how much leaves the basin in the discharge of the main trunk channel. Streams are arranged in an orderly fashion in drainage basins, with progressively smaller channels branching away from the main trunk channel. Stream channels are ordered and numbered according to this systematic branching. The smallest segments lack tributaries and are known as first-order streams; second-order streams form where two first-order streams converge; third-order streams form where two second-order streams converge, and so on.

Streams within drainage basins develop characteristic branching patterns that reflect, to some degree, the underlying bedrock geology, structure, and rock types. Dendritic or randomly branching patterns form on horizontal strata or on rocks with uniform erosional resistance. Parallel drainage patterns develop on steeply dipping strata, or on areas with systems of parallel faults or other landforms. Trellis drainage patterns consist of parallel main stream channels intersected at nearly right angles by tributaries, in turn fed by tributaries parallel to the main channels. Trellis drainage patterns reflect significant structural control, and typically form where eroded edges of alternating soft and hard layers are tilted, as in folded mountains or uplifted coastal strata. Rectangular drainage patterns form a regular rectangular grid on the surface, and typically form in areas where the bedrock is strongly faulted or jointed. Radial and annular patterns develop on domes including volcanoes and other roughly circular uplifts. Other, more complex patterns are possible in more complex situations, as illustrated by multibasinal and contorted styles of drainage patterns.

Several categories of streams in drainage basins reflect different geologic histories. A consequent stream is one whose course is determined by the direction of the slope of the land. A subsequent stream is one whose course has become adjusted so that it occupies a belt of weak rock or another geologic structure. An antecedent stream is one that has maintained its course across topography being uplifted by tectonic forces; these cross high ridges. Superposed streams are those whose courses were laid down in overlying strata onto unlike strata below. Stream capture occurs when headland erosion diverts one stream and its drainage into another drainage basin.

EFFECTS OF RIVER MODIFICATIONS ON RIVER DYNAMICS

The long history of flooding and attempted flood-control measures along the Mississippi River basin had taught engineers valuable lessons on how to manage flood control on river basins. Levees are commonly built along riverbanks to protect towns and farmlands from river floods. These levees usually succeed at the job they were intended to do, but they also cause other collateral effects. First, the levees do not allow waters to spill onto the floodplains, so the floodplains do not receive the annual fertilization by thin layers of silt, and they may begin to deflate and slowly degrade as a result of this loss of nourishment by the river. The ancient Egyptians relied on such yearly floods to maintain their fields' productivity, which has declined since the Nile has been dammed and altered in recent times. Another effect of levees is that they constrict the river to a narrow channel, so that floodwaters that once spread slowly over a large region are now focused into a narrow space. This causes floods to rise faster, reach greater heights, have a greater velocity, and reach downstream areas faster than rivers without levees. The extra speed of the river is in many cases enough to erode the levees and return the river to its natural state.

One of the less appreciated effects of building levees on the sides of rivers is that they sometimes cause the river to slowly rise above the height of the floodplain. Many rivers naturally aggrade or accumulate sediment along their bottoms. In a natural system without levees this aggradation is accompanied by lateral or sideways migration of the channel so that the river stays at the same height with time. If a levee is constructed and maintained, however, the river is forced to stay in the same location as it builds up its bottom. As the bottom rises, the river naturally adds to the height of the levee, and people will also build up the height of the levee as the river rises to prevent further flooding. The net result is that the river may gradually rise above the floodplain, until some catastrophic flood causes the levee to break, and the river establishes a new course.

Breaking through a levee happens naturally as well and is known as avulsion. Avulsion has occurred seven times in the last 6,000 years along the lower Mississippi River. Each time the river has broken through a levee a few hundred miles from the mouth of the river and has found a new, shorter route to the Gulf of Mexico. The old river channel and delta is then abandoned, and the delta subsides below sea level, as the river no longer replenishes it. A new channel is established and this gradually builds up a new delta until it too is abandoned in favor of a younger, shorter channel to the gulf.

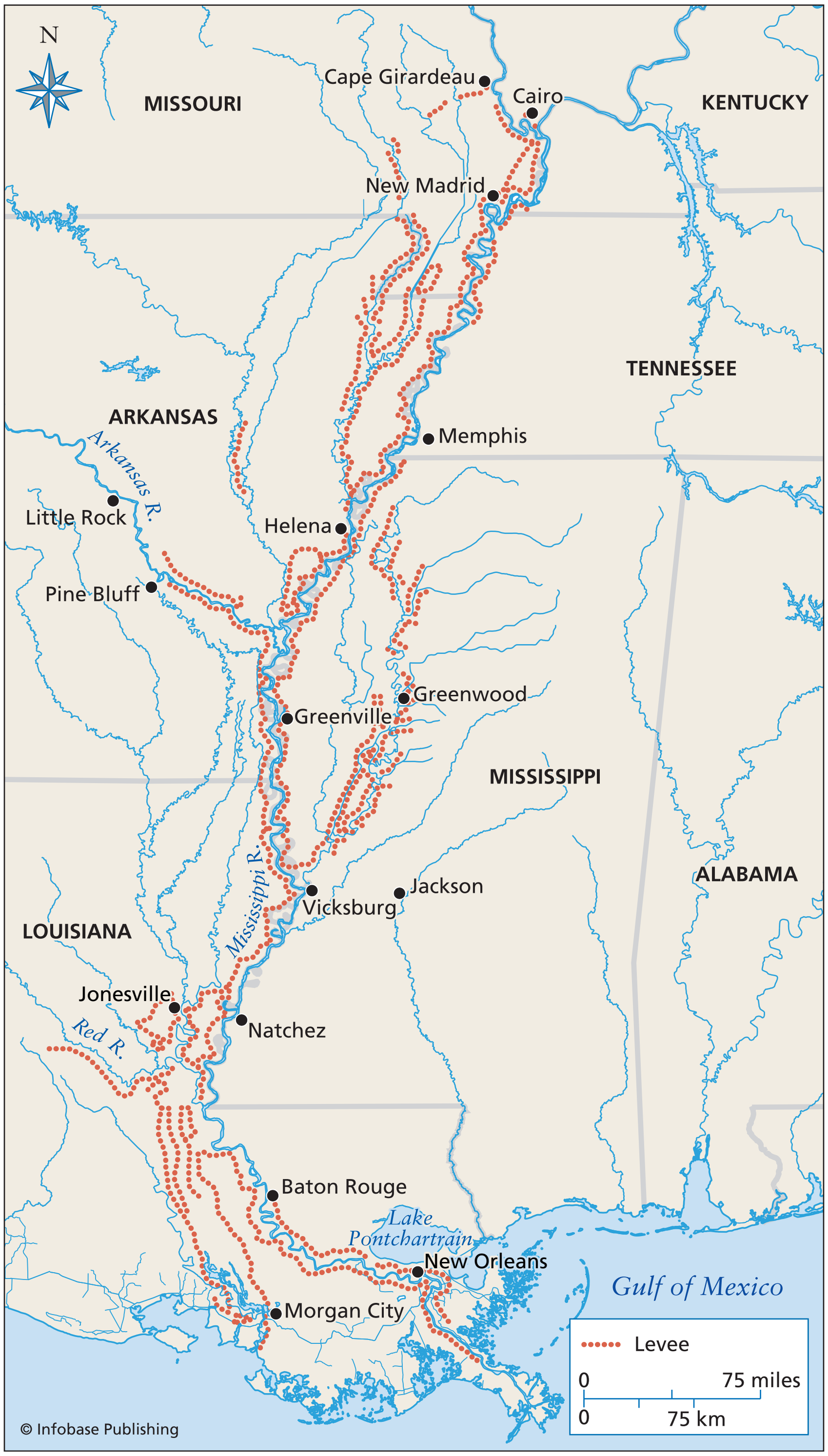
The history of constructing levees along the Mississippi River is instructive as it illustrates how the dynamics of the river were not appreciated as the course of the river was being altered, and levees were constricting the flow in efforts to reduce flooding and increase navigability. By the time engineers realized the consequences of constricting the river, a couple of hundred years of river modifications had already taken their toll. Still, further modifications were proposed and implemented, and the floods continue to worsen.

History of Levee Building on the Mississippi River

The Mississippi River is the longest river in the world and encompasses the third-largest watershed, draining 41 percent of the continental United States including an area of 1,245,000 square miles (3,224,550 km^2). The river transports 230 million tons of sediment, including the sixth-largest silt load in the world. Before the Europeans came and began altering the river, this silt used to cover the floodplains with this fertile material during the semiannual floods and carry more downriver to be deposited on the Mississippi River delta. Levee construction along the lower Mississippi River system began with the first settlers who came to the region, and has continued until the present-day levee system, the main parts of which include 2,203 miles (3,580 km) of levees, flood walls, and other control structures. Of this, 1,607 miles (2,586 km) of levees lie along the Mississippi River, and another 596 miles (959 km) are along the banks of the Arkansas and Red Rivers in the Atchafalaya basin. Additional levees are built along the Missouri River.

The first levee along the Mississippi River was built around the first iteration of New Orleans between 1718 and 1727, and consisted of a slightly more than mile-long (5,400 feet; 1,646 m), 4-foot-high earthen mound that was 18 feet (5.5 m) wide at the top, with road along the crown. This levee was meant to protect the residents of the newly founded city from annual floods and pestilence that would last from March until June of each year. New Orleans had only recently been inhabited—Louis XIV of France had commissioned the explorer Pierre Le Moyne, Sieur d'Iberville, to establish a colony near the mouth of the Mississippi River to control the Mississippi valley and the lumber and fur trade moving down the river. D'Iberville's younger brother, Jean Baptiste Le Moyne, Sieur de Bienville, established New Orleans in 1718 in a bend of the river to control the portage between the river and Lake Pontchartrain. The site of New Orleans was surrounded by water on all sides. Lakes Ponchartrain, Maurepas, and Bayou Manchac and the Amite River divide it from higher land on the north, and the Mississippi River wraps around its other sides. The site of New Orleans on the natural levee of the Mississippi on the Isle of Orleans has always been precarious, and the city has been inundated by floods from the river on three sides, and by storm surges from hurricanes on the other side about every 30 years since its founding. The first levee built in 1718–27 did not stop the floods, and the city was destroyed by a hurricane in 1722. On September 23–24 a hurricane almost completely destroyed the newly founded capital city. The storm had 100-mile-per-hour (161 kph) sustained winds and a storm surge of 7–8 feet (2–2.4 m) that overtopped the four-foot (1.2-m) high levee. Almost every building in the city was destroyed or severely damaged. If city planners has taken this warning when the city consisted only of several dozens of buildings, much future damage could have been avoided. Instead, more and higher levees were built, with successive floods by storms destroying or severely damaging the city in 1812, 1819, 1837, 1856, 1893, 1909, 1915, 1947, 1956, 1965, 1969, and 2004. The old levees did not hold in 1722, the new levees did not hold in 2004 during Hurricanes Katrina and Rita, and the levees broke repeatedly during the high-water events in between.

The early river levees along the Mississippi consisted of earthen mounds, generally with a slope of 1:2. The local and state governments made it a policy that local farmers had to build their own levees on the property they owned along the Mississippi. Haul methods for bringing the dirt to make the levees were primitive, typically with horse and carriage, yielding only 10–12 cubic yards (7.5–9 m^3) per day. The federal government became involved in 1820 with legislation that focused mostly on navigation along the river and did not consider flood control. As the levees were built at breakneck pace, the river became constricted, causing the bed of the river to raise itself continuously in a process called aggradation. This happens because if the river is not allowed to migrate laterally, it cannot move out of the way of the sediment it is carrying and depositing, and cannot widen the channel, so therefore it raises the bed as this sediment is deposited. Disastrous floods along the lower Mississippi in 1844, 1849, and 1850 resulted in passage of the Swamp Acts of 1849 and 1850. These acts gave Louisiana, Mississippi, Arkansas, Missouri, and Illinois swamp and overflow lands within their boundaries that were unfit for cultivation. These lands were sold, and the revenues generated were used to construct levees and complete drainage reclamation of the purchased lands. Between 1850 and 1927 the levees along the lower Mississippi had to be continuously heightened because of this river avulsion caused by the construction of the levees.



Map of the lower Mississippi River from the mouth of the delta to southern Missouri showing the thousands of miles of levees constructed along the river in the past century

In 1850 Congress appropriated $50,000 to complete two topographic and hydrographic surveys to promote flood protection along the Mississippi River. One survey was completed by a civilian engineer, Charles Ellet Jr., and the other by army engineers A. A. Humphreys and Henry Abbot. The Humphreys-Abbot report recommended three possible methods for flood control including cutting off the bends in the river, diversion of tributaries creating artificial reservoirs and outlets, and confining the river to its channel using levees. Since the first two options were considered too expensive, the third was enacted, with long-lasting consequences. Their levee design called for freeboards at 3–11 feet (1–3.4 m) above the level of the 1858 flood.

The Civil War (1861–65) saw the levees disregarded and they fell into a state of disrepair, made worse by the large floods of 1862, 1865, and 1867. New floods in 1874 prompted the creation of a Levee Commission to complete a new survey of the state of the levees and recommend how to repair the system and reclaim the floodplain. The Levee Commission made a stark assessment, citing major defects in the system and huge costs to repair and improve it. They documented that previous levees were built in faulty locations, with poor organization, insufficient height, poor construction, and inadequate inspection and guarding. They estimated that it would cost $3.5 million to repair the existing system and $46 million to build a new, complete levee system to reclaim the floodplain from the river.

In 1879 Congress created the Mississippi River Commission (MRC), as organized by James B. Eads.

The commission consisted of three officers from the U.S. Army Corps of Engineers, three civilians, and one officer from the U.S. Coast and Geodetic Survey. The MRC conducted surveys and suggested many modifications and new additions to the flood-control and navigation projects along the river. They made a policy in 1882 to close the breaks along the levee and to construct a line of levees with sufficient height and grade supposedly to contain the frequent floods along the river. They did not have long to wait to see the faults in their model.

The flood of 1890 destroyed 56 miles (90 km) of levees, and the MRC began to raise the levees from 38 to 46 feet (11.5 m to 14 m). During this phase of massive reconstruction the federal government and private citizens added more than 125 million cubic yards of soil to the levees (96 million m^3), but much of this was lost to the river by mass wasting processes including slumping and bank caving. Efforts were made to reinforce the banks with various revetments, but then the flood of 1912 destroyed much of the levee system that was meant to protect the adjacent floodplain. The response of the commission was to raise the levees again, to three feet above the 1912 flood line. The lesson was not yet learned that raising the levee and constricting the river causes the bed to aggrade and rise as well.

The first federal flood control act was passed in 1917, authorizing for the first time levees to be built for flood control, along both the Mississippi and its tributaries. The federal government would pay two-thirds of the costs of levees if the local interests would pay the balance. During the 1920s levee construction was stepped up to a higher pace with the mechanization of earth-moving technology, with introduction of large cranes, moving tower machines, and cableway draglines that could move dirt orders of magnitude faster than the traditional horse and cart.

The year 1927 came, and with it, the greatest flood in recorded history along the lower Mississippi River valley. Many of the levees built to the MRC standards failed up and down the river, with enormous consequences in terms of loss of life, displaced people, and loss of property that was supposed to be protected by the levees. The government responded with the 1928 Flood Control Act, passing legislation to improve the grade of the levees and make models of different flood scenarios, including the creation of several large floodways that could be opened to let water out of the river in high flow times. Some of these floodways were quite large, such as the Birds Point–New Madrid floodway, which is about 35 miles (56 km) long, 3–10 miles (5–16 km) wide, and designed to divert 550,000 cubic feet (15,576 m^3) per second of flow from the Mississippi during floods. Further downriver the West Atchafalaya floodway was designed to carry half of the modeled projected flood of 1,500,000 cubic feet (139,400 m^3) per second. The Bonne Carre floodway was built upriver from New Orleans, designed to restrict the flow to downstream by diverting the water and protecting New Orleans. Levees were redesigned, moved to locations where their projected life span was from 20 to 30 years, and thought to be stronger. As construction on the new levee and floodway system continued, new floods, such as the 1929 flood, disrupted operations, but the construction methods continued to improve, and the levees were built, forming much of the present-day levee system.

In 1937 a large flood emanated from the Ohio River watershed, raising the waters to levels such that the Birds Point–New Madrid floodway was used, opening the floodway by dynamiting the Fuse Plus levee. This released huge volumes of water and eased the flood downstream. One of the lessons from the 1937 flood was that roads should be added to the levees to aid in moving material from place to place during floods. In 1947 the MRC began redesigning levees to be stronger to avoid failure, recognizing the importance of compaction for reducing the chances of levee failure.

Levees fail by three main modes: underseepage of water beneath the levee, where the pressure from the high water opens a channel causing catastrophic failure; hydraulic piping, in which the water finds a weak passage through the levee; and overtopping when the water flows over the top of the levee and erodes the sides. Levees can also fail when the river current scours the base of the levee during high-flow conditions, as happened in many of the Mississippi River floods, and this causes slumping and massive collapse of the levee. Mass wasting is also promoted by long-term floods in which the water gradually saturates the pores of the levee, weakening it, causing massive liquefaction and catastrophic failure, leading large sections of the levee to collapse at the same time. Most levee failures happen during times when the flow has been high for long periods, since this increases the pore pressure, scouring, and liquefaction potential of the levee.

By 1956 the MRC was modeling floods with twice the previous discharge, examining the ability of the river and levee system to handle a discharge of 3,000,000 cubic feet (2,300,000 m^3) per second. Then the flood of 1973 hit the Mississippi River basin with one of the highest floods recorded in 200 years. The flood set a record for the number of days the river was out of bank, causing more than $183,756,000 in damages. In terms of flood management, the flood of 1973 brought the realization that building levees, wing dikes, and other navigational and so-called flood-control measures had actually decreased the carrying capacity of the river. This meant that for any given amount of water, the flood levels (called stages) would be higher than before the levees were built.

The catastrophic floods of 1993 provided another test of the levees, and the new system failed massively. The constriction of the river caused by the levees led to numerous cases of levee failure, overtopping, crevasse splays, collapse, and massive amounts of damage as had never been seen along the river. Approximately two-thirds of all the levees in the upper Mississippi River basin collapsed, were breached, or were otherwise damaged by the floods of 1993. Dozens of people died and 50,000 homes were damaged or destroyed, with total damage estimated at most than $15 billion.

SUMMARY

Streams are dynamic systems that represent a balance between the forces that drive the current and those that resist the flow. Channels have many different styles that form in response to a quasi equilibrium between the gradient, or slope, of the streambed, the discharge of the stream, the amount of sediment being transported, the roughness of the streambed, and the resistance of the bank to erosion. The stream may form one of three main types of channels in response to the relative contributions of these variables. Straight channels are the rarest and are usually controlled by incision into a bedrock structure, but within the straight channel the current usually follows a curved path. Meandering streams are most common, with the current actively eroding cut banks and depositing material on the opposite point bars. In this way the meanders move back and forth across the floodplain, maintaining equilibrium through changes in the sinuosity, meander wavelength, width and depth of the channel, and velocity of the current. Meandering channels and their floodplains are different parts of the same dynamic system. Braided streams have multiple channels and are prone to rapid changes; they carry more sediment than meandering or straight channels. They are prone to large fluctuations in discharge and load, and many are found in environments in front of melting glaciers.

Individual stream and river channels are parts of much larger systems, and the patterns of branching and angles between individual streams often define different patterns that reflect underlying processes. Some river systems exhibit control by uniform slopes; some have rectilinear patterns reflecting underlying beds and structures; some are radial, reflecting drainage off domes; and others cut straight through uplifted mountain ranges. The regional pattern of the stream channels reflects control by the underlying geology, and the more local stream channel pattern reflects control by the balance between the forces driving the current and those opposing it. Streams can deposit thick layers of sand, mud, and gravel on floodplains, cut through them forming terraces, and carry massive amounts of sediment to the sea to deposit them as giant delta complexes. These delta complexes build to sea and have forms that reflect a balance among sediment input, tides, and wave energy. Many delta lobes are active on the order of 1,000 years; then the river switches course and forms a new lobe, as the older one subsides.

See also DRAINAGE BASIN (DRAINAGE SYSTEM); FLOOD; RIVER SYSTEM; SEDIMENTARY ROCK, SEDIMENTATION.

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flysch Flysch is a syn-orogenic clastic sedimentary deposit typically marked by interbedded shales and sandstones. The term was first used for sedimentary rocks deposited in the Alps in Cretaceous-Tertiary times, before the main erosional event that shed coarser-grained conglomerates known as molasse. Sedimentary structures in flysch typically include a series of graded and cross-laminated layers in sands forming Bouma sequences, indicating that the sands were deposited by turbidity currents. Flysch is typically deposited in foreland basins and forms regionally extensive clastic wedges, underlain by distal black shales and overlain by fluvial deposits and conglomerates of fluvial origin.

The most common type of sedimentary deposit in flysch sequences are turbidite sequences. A turbidite is a deposit of a submarine turbidity current consisting of graded sandstone and shale, typically deposited in a thick sequence of similar turbidites. Most turbidites are thought to be deposited in various subenvironments of submarine fans, in shallow- to deep-water settings. These form when water-saturated sediments on a shelf or in a shallow water setting are disturbed by a storm, earthquake, or some other mechanism that triggers the sliding of the sediments down slope. The sediment-laden sediment/water mixture then moves rapidly down slope as a density current, and may travel tens or even hundreds of miles at tens of miles per hour until the slope decreases

Alternating sandstone and shale deposits arranged in an anticline fold in flysch sediments in Zumaia, Spain *(Dirk Wiersma/Photo Researchers, Inc.)*

and the velocity of current decreases. As this occurs the ability of the current to hold coarse material in suspension decreases, and the current drops, first, its coarsest load, and then progressively finer material as the current velocity continues to decrease. In this way the coarsest material is deposited closest to the channel or slope that the turbidity current flowed down, and the finest material is deposited further away. The same sequence of coarse to fine material is deposited upward in the turbidite bed as the current velocity decreases with time at any given location. This is how graded beds are formed, with the coarsest material at the base and finer material at the top.

Classical complete turbidite beds consist of a sequence of sedimentary structures divided into a regular A-E sequence known as the Bouma sequence, after the sedimentologist Arnold Bouma, who first described the sequence. The A horizon consists of coarse- to fine-grained graded sandstone beds, representing material deposited rapidly from suspension. The B horizon consists of parallel-laminated sandstones deposited by material that moved in traction on the bed, whereas division C contains cross-laminated sands deposited in the lower-flow regime. The D and E horizons represent the transition from material deposited from the waning stages of the turbidity current and background pelagic sedimentation.

Variations in the thickness and presence or absence of individual horizons of the Bouma sequence have been related to where on the submarine fan or slope the turbidite was deposited. Turbidites with more of the A-B-C horizons are interpreted to have been deposited closer to the slope or channel, whereas turbidites sequences with more of the C-D-E horizons are interpreted as more distal deposits.

Many turbidite sequences are deposited in foreland basins and in deep-sea trench settings. These environments have steep slopes in the source areas, a virtually unlimited source of sedimentary material, and many tectonic triggers to initiate the turbidity current.

Molasse sequences overlie many turbidite-bearing flysch sequences, especially those deposited in foreland basins. Molasse consists of thick sequences of coarse-grained postorogenic sandstones, conglomerates shales, and marls that form in response to the erosion of orogenic mountain ranges. The name is derived from the classic Miocene-Oligocene-Pliocene molasse of the European foreland, deposited across much of France, Switzerland, and Germany, and overlying the Alpine flysch sequence. These sediments are up to four miles (7 km) thick on the Swiss Plateau and represent rapid erosion of the Alps. Lower parts of the molasse include shallow marine and tidally influenced sediments, overlain by alluvial fan deltas, alluvial fan complexes, and overbank deposits.

See also BASIN, SEDIMENTARY BASIN; CONVERGENT PLATE MARGIN PROCESSES; OROGENY; SEDIMENTARY ROCK, SEDIMENTATION.

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fossil A fossil is any remains, trace, or imprint of any plant or animal that lived on the Earth. Such remains of past life include body fossils, the preserved record of hard or soft body parts, and trace fossils that record traces of biological activity such as footprints, tracks, and burrows. The oldest body fossils known are 3.4 billion-year-old remnants of early bacteria, whereas chemical traces of life may extend back to 3.8 billion years.

The conditions that lead to fossilization occur so rarely that a mere 10 percent of all species that have ever existed are estimated to be preserved in the fossil record. The record of life and evolution is therefore very incomplete. To be preserved life-forms become mineralized after they die, with organic tissues typically being replaced by calcite, quartz, or other minerals during burial and diagenesis. Fossils are relatively common in shallow marine carbonate rocks where organisms that produced calcium carbonate shells are preserved in a carbonate matrix.

The fossil record has been used to test, modify, and support evolution, a concept traditionally regarded as a slow, gradual process that describes how life has changed with time on the Earth, starting with simple single-celled organisms to the complex biosphere on the planet today. However, a better definition for biological evolution is a sustained change in the genetic makeup of populations over a period of generations leading to a new species. The field of evolution was pioneered by Charles Darwin in his *Origin of Species* (1859) and *The Descent of Man* (1871) and is a multidisciplinary science incorporating geology, paleontology, biology, and, with neo-Darwinism, genetics.

Darwin sailed on the HMS *Beagle* (1831–36) when he made numerous observations of life and fossils from around the world, leading to the development of his theory of natural selection, in which species with favorable traits stand a better chance for survival. The main tenets of his theory are that species reproduce more than necessary, but populations tend to remain stable since there is a constant struggle for food and space, and only the fittest survive. Darwin proposed that the traits that contributed to an individual's survival are passed on to its descendants, hence propagating the favorable traits. But Darwin did not have a good explanation for why some individuals would have favorable traits that others would not. This evidence would not come until much later with the field of genetics and the recognition that mutations can cause changes in character traits. Sequential passing down to younger generations of mutation-induced changes in character traits can lead to changes in the species and, eventually, the evolution of new species. Darwin's process of natural selection works by the gradual elimination of the less successful forms of species, favoring the other forms that had favorable mutations.

More modern variations on evolution recognize two major styles of change. Macroevolution describes changes above the species level and the origin of major groups, whereas microevolution is concerned with changes below the species level and the development of new species. Another major development in the field of evolution over the past century relates to the rate of evolutionary changes as preserved in the fossil record. Darwin thought that evolution progressed slowly, with one species gradually changing into a new species, but the fossil record supports only a few examples of this gradual change (notable examples include changes in trilobites in the Ordovician and changes in horses in the Cenozoic). Fossil evidence demonstrates the persistence of nearly all species with little change for long periods of geologic time, followed by a sudden disappearance and subsequent replacement with entirely new species. In other cases new species suddenly appear without the disappearance of other species. Biologists initially regarded skeptically some of the apparent rapid change in an incomplete fossil record, but many examples of complete records show that these rapid changes are real. A new paradigm of evolution named punctuated equilibrium, advanced in the 1970s by Steven Jay Gould and Niles Eldredge, explains these sudden evolutionary changes. Physical or geographic isolation of some members of a species, such as expected during supercontinent breakup, can separate and decimate the environment of a species and effectively isolate some of its members in conditions that can select for change. This small group may have a mutation that favors their new environment, letting them survive. When supercontinents collide, many species that never encountered one another must compete for the same food and space, and only those best suited to that particular environment will survive to reproduce, leading to extinction of the others.

In other cases major environmental catastrophes such as meteorite impacts and flood basalt eruptions can cause extreme changes in the planetary environment, causing mass extinction. Relatively minor or threatened species that survive can suddenly find themselves with traits that favor their explosion into new niches and their dominance in the fossil record.

See also EVOLUTION; LIFE'S ORIGINS AND EARLY EVOLUTION; MASS EXTINCTIONS; PALEONTOLOGY; SUPERCONTINENT CYCLES.

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fracture A general name for a break in a rock or other body that may or may not have any observable displacement. Fractures include joints, faults, and cracks formed under brittle deformation conditions and are a kind of permanent (nonelastic) strain. Brittle deformation processes generally involve the growth of fractures or sliding along existing fractures. Frictional sliding involves the sliding on preexisting fracture surfaces, whereas cataclastic flow includes grain-scale fracturing and frictional sliding producing macroscopic ductile flow over a band of finite width. Tensile cracking involves the propagation of cracks into unfractured material under tensile stress perpendicular to the maximum compressive stress, whereas shear rupture refers to the initiation of fracture at an angle to the maximum principal stress.

Fractures may propagate in one of three principal modes. Mode I refers to fracture growth by incremental extension perpendicular to the plane of the fracture at the tip. In Mode II propagation is where the fracture grows by incremental shear parallel to the plane of the fracture at the tip, in the direction of fracture propagation. Mode III is when the fracture grows by incremental shear parallel to the plane of the fracture at the tip, perpendicular to the direction of propagation.

Joints are fractures with no observable displacement parallel to the fracture surface. They generally occur in subparallel joint sets, and several sets often occur together in a consistent geometric pattern, forming a joint system. Joints are sometimes classified into extension joints or conjugate sets of shear joints, a subdivision based on the angular relationships between joints. Most joints are continuous for only short distances, but in many regions master joints may run for long distances and control geomorphology or form air photo lineaments. Microfractures or joints are visible only under the microscope and affect only a single grain.

Many joints are contained within individual beds and have a characteristic joint spacing, measured perpendicular to the joints. This is determined by the relative strength of individual beds or rock types, the thickness of the jointed layer, and structural position, and is very important for determining the porosity and permeability of the unit. In many regions fractures control groundwater flow; location of aquifers, and migration and storage of petroleum and gas.

Joints and fractures, found in all kinds of environments, form by a variety of mechanisms. The contraction of materials induces the formation of desiccation cracks and columnar joints. Mineral changes during diagenesis that lead to volume changes in the layer produce bedding plane fissility, characterized by fracturing parallel to bedding. Unloading joints form by stress release, such as during uplift, ice sheet withdrawal, or quarrying operations. Exfoliation joints and domes may form by mineral changes, including volumetric changes during weathering, or by diurnal temperature variations. Most joints have tectonic origins, typically forming in response to the last phase of tectonic movements in an area. Other joints seem to be related to regional doming, folding, and faulting.

Many fractures and joints exhibit striated or ridged surfaces known as plumose structures, since they vaguely resemble feathers. Plumose structures develop in response to local variations in propagation velocity and the stress field. The origin is the point at which the fracture originated, the mist is the small ridging on the surface, and the plume axis is the line that starts at the axis and from which individual barbs propagate. The twist hackle refers to the steps at the edge of the fracture plane along which the fracture has split into a set of smaller en echelon fractures.

British geologist E. M. Anderson elegantly explained the geometry and orientation of some fracture sets in 1905 and 1942, and in a now classic work published in 1951, *The Dynamics of Faulting and Dyke Formation*. General acceptance of this model by the scientific community led to Anderson's model being adopted, and many fault and fracture sets are described in terms of Anderson's theory. According to Andersonian theory the attitude of a fracture plane tells a lot about the orientation of the stress field that operated when the fracture formed. Fractures are assumed to form as shear fractures in a conjugate set, with the maximum compressive stress bisecting an acute (60°) angle between the two fractures. In most situations the surface of the Earth may be the maximum, minimum, or intermediate principal stress, since the surface can transmit no shear stress. If the maximum compressive stress is vertical, two fracture sets will form, each dipping 60° toward each other and intersecting along a horizontal line parallel to the intermediate stress. If the intermediate stress is vertical, two vertical fractures will form, with the maximum compressive stress bisecting the acute angle between the fractures. If the least compressive stress is vertical, two gently dipping fractures will form, and their intersection will be parallel to the intermediate principal stress.

Other interpretations of fractures and joints include modifications of Andersonian geometries that include volume changes and deviations of principal stresses from the vertical. Many joints show relationships to regional structures such as folds, with some developing parallel to the axial surfaces of folds and others crossing axial surfaces. Other features on joint surfaces may be used to interpret their mode of formation. For instance, plumose structures typically indicate Mode I or extensional types of formation, whereas the development of fault striations (known as slickensides) indicates Mode II or Mode III propagation. Observations of these surface features, the fractures' relationships to bedding, structures such as folds and faults, and their regional orientation and distribution can lead to a clear understanding of their origin and significance.

FRACTURE ZONE AQUIFERS

Fractures and joints are in many places important aquifers, forming deep spaces in the Earth where water can be stored without evaporation or contamination for centuries or even thousands of years. Faults and fractures develop at various scales from faults that cross continents to fractures that are visible only microscopically. The internal properties of the rock and the external stresses imposed on it determine the location and orientation of these discontinuities in the rock fabric. Fractures at various scales represent zones of increased porosity and permeability. By forming networks they are able to store and carry vast amounts of water.

The concept of fracture zone aquifers explains the behavior of groundwater in large fault-controlled watersheds. Fault zones in this case serve as collectors and transmitters of water from one or more recharge zones with surface and subsurface flow strongly controlled by regional tectonism.

Both the yield and quality of water in these zones are usually higher than average wells in any type of rock. High-grade water for such a region would be 250 gallons (950 liters) per minute or greater. In addition the total dissolved solids measured in the water from such high-yielding wells will be lower than the average for the region.

The fracture zone aquifer concept looks at the variations in groundwater flow as influenced by secondary porosity over an entire watershed. It attempts to integrate data on a basin in an effort to describe the unique effects of secondary porosity on the processes of groundwater flow, infiltration, transmissivity, and storage.

The concept includes variations in precipitation over the catchment area. One example is orographic effects wherein the mountainous terrain precipitation is substantially greater than at lower elevations. The rainfall is collected over a large catchment area, which contains zones with high permeability because of intense bedrock fracturing associated with major fault zones. The multitude of fractures within these highly permeable zones "funnel" the water into other fracture zones that are down gradient from where the water enters the system. These funnels may be in a network of hundreds of square miles (kilometers).

The fault and fracture zones serve as conduits for groundwater and often act as channelways for surface flow. Intersections form rectilinear drainage patterns sometimes exposed on the surface but are also represented below the surface and converge down the hydrologic gradient (at places to which water would flow naturally downhill). In some regions these rectilinear patterns are not always visible on the surface owing to vegetation and sediment cover. The convergence of these groundwater conduits increases the amount of water available as recharge. The increased permeability, water volume, and ratio of water to minerals within these fault/fracture zones help to maintain the quality of water supply. These channels occur in fractured, nonporous media (crystalline rocks) as well as in fractured, porous media (sandstone, limestone).

At some point in the groundwater course, after convergence, the gradient decreases. The sediment cover over the major fracture zone becomes thicker and acts as a water storage unit with primary porosity. The major fracture zone acts as both a transmitter of water along conduits and a water storage basin along connected zones with secondary (and/or primary) porosity. Groundwater within this layer or lens often flows at accelerated rates. The result can be a pressurization of groundwater both in the fracture zone and in the surrounding material. Precipitation can almost instantaneously replenish the rapid flow in the conduit. The surrounding materials are replenished more slowly, but also release the water more slowly and serve as a storage unit to replenish the conduit between precipitation events.

Once the zones are saturated, any extra water that flows into them will overflow, if an exit is available. In a large-area watershed it is likely that this water flows along subsurface channelways under pressure until some form of exit is found in the confining environment. Substantial amounts of groundwater may flow along an extension of the main fault zone controlling the watershed and may vent at submarine extensions of the fault zone, forming coastal or offshore freshwater springs.

The concept of fracture zone aquifers is particularly applicable to areas underlain by crystalline rocks and where these rocks have undergone a multiple deformational history that includes extensional tectonics. This is especially true for areas where recharge is possible from seasonal and/or sporadic rainfall on mountainous regions adjacent to flat desert areas.

Fracture zone aquifers are distinguished from horizontal aquifers in that (a) they drain numerous wadis in extensive areas and many extend for tens of miles (dozens of kilometers); (b) they constitute conduits to mountainous regions where the recharge potential from rainfall is high; (c) some may connect several horizontal aquifers and thereby increase the volume of accumulated water; (d) because the source of the water is at higher elevations, the artesian pressure at the groundwater level may be high; and (e) they are usually missed by conventional drilling because the water is often at the depth of up to 1,000 feet (hundreds of meters).

The characteristics of fracture zone aquifers make them an excellent source of groundwater in arid and semiarid environments. Fracture zone aquifers are located by seeking major faults. The latter are usually clearly displayed in images obtained from spacecraft in Earth's orbit, because they are emphasized by drainage. Thus the first step in evaluating the groundwater potential of any region is to study the structures displayed in satellite images to map the faults, fractures, and linear features of uncertain origin (called lineaments). Such a map is then compared with a drainage map showing wadi locations. The combination of many wadis and major fractures indicates a larger potential for groundwater storage. Furthermore, the intersection between major faults would increase both porosity and permeability and, hence, the water-collection capacity.

Groundwater resources in arid and semiarid lands are scarce and must be properly used and thoughtfully managed. Most of these resources are "fossil," having accumulated under wet climates during the geological past. The present rates of recharge from the occasional rainfall cannot sufficiently replenish the aquifers. Therefore the resources must be used sparingly without exceeding the optimum pumping rates for each water well field.

See also DEFORMATION OF ROCKS; GROUNDWATER; STRUCTURAL GEOLOGY.

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G

Gaia hypothesis The British atmospheric chemist James Lovecock proposed the Gaia hypothesis in the 1970s, suggesting that Earth's atmosphere, hydrosphere, geosphere, and biosphere interact as a self-regulating system that maintains conditions necessary for life to survive. In this view the Earth acts as if it is a giant self-regulating organism in which life creates changes in one system to accommodate changes in another to keep conditions within the narrow limits that allow life to continue on Earth.

The temperature on the Earth has been maintained at 50°–86°F (10°–30°C) for the past 3.5 billion years, even though the solar energy received by the Earth has increased by 40–330 percent since the Hadean. The temperature balance has been regulated by changes in the abundance of atmospheric greenhouse gases, controlled largely by volcanic degassing and the reduction of carbon dioxide (CO_2) by photosynthetic life. A slight increase or decrease in CO_2 and other greenhouse gases could cause runaway greenhouse or icehouse global climates, yet life has been able to maintain the exact balance necessary to guarantee its survival.

The presence of certain gases such as ammonia at critical levels in the atmosphere for maintaining soil pH near 8, the optimal level for sustaining life, is critical for maintaining atmospheric oxygen levels. This critical balance is unusual, as methane is essentially absent from the atmospheres of Venus and Mars, where life does not exist. The salinity of the oceans has been maintained at around 3.4 percent, in the narrow range required for marine life, reflecting a critical balance between terrestrial weathering, evaporation, and precipitation.

The exact mechanisms that the Earth maintains for these critical balances necessary for life are not well known. As solar luminosity increases, however, the additional energy received by the Earth is balanced by the amount of energy radiated back to space. Changes in the surface reflectance (albedo) can accomplish this through changes in the amount of ice cover, types of plants, and cloud cover. Changes in one Earth system produce corresponding changes in other systems in self-regulation processes known as homeostasis. Critical for Gaia are the links between organisms and the physical environment, such that many proponents of the theory regard the planet as one giant superorganism.

See also ATMOSPHERE; CLIMATE; CLIMATE CHANGE; GREENHOUSE EFFECT; SUPERCONTINENT CYCLE.

galaxies Galaxies are gravitationally bound assemblages of stars, dust, gas, radiation, and dark matter. Most contain vast numbers of star systems and are located at enormous distances from our Milky Way Galaxy, such that the light reaching Earth from these galaxies was generated billions of years ago.

TYPES OF GALAXIES

Telescopic observations of galaxies show that they have a wide range of different shapes first classified by the American astronomer Edwin Hubble in 1924 into four basic types, including spiral galaxies, barred spiral galaxies, elliptical galaxies, and irregular galaxies. Hubble's classification has since been modified and elaborated upon, but astronomers continue to use the same basic scheme.

Spiral galaxies are characterized by a flattened disk shape that exhibits a central bulge and spiral-shaped arms that emerge from this central bulge and extend in variously curved forms to distant reaches of the galaxy. These are surrounded by a galactic halo made of a ball of old faint stars forming a sphere around the other parts of the galaxy. The Milky Way, which contains billions of star and planetary systems, including Earth, is a spiral galaxy. One of the major differences between different types of spiral galaxies is how tightly wrapped the spiral arms are as they circle the bulge in the core of the galaxy. Generally, the larger the central bulge of the galaxy, the more tightly wrapped the arms become. Galaxies with small central bulges in their cores tend to have loosely wrapped spiral arms and more lumpy or knotty distributions of matter within their arms. In the Hubble classification, forms of spiral galaxies are abbreviated by the letter *S,* with small letters *a-d* denoting progressively more open spiral forms, such that Sc galaxies are more open than Sa galaxies.

Most spiral galaxies have galactic disks rich in gas and dust, and halos comprised largely of old dim stars. The spiral arms have many younger stars and newly forming star systems and are the densest parts of these galaxies, providing material for the birth of new star systems.

Barred spirals are a special class of spiral galaxies in which a concentrated "bar" of stellar and interstellar matter passes through the central bulge of the galaxy, and the spiral arms extend from the ends of this bar. Most of these have unusual shapes, resembling giant Z or S shapes, with spiral trails of luminous matter extending around the letter. Barred spiral galaxies are designated by the Hubble classification as SB galaxies, with the small letters *a-c* denoting how open the spiral arms are around the bar.

Elliptical galaxies are circular to highly elliptical concentrations of stellar and interstellar matter whose density increases toward the center of the galaxies. The size of elliptical galaxies and the number of stars contained within elliptical galaxies vary widely. Some are small and known as dwarf ellipticals, being only a kiloparsec across and containing on the order of a million stars. Others are huge, many times the size of the Milky Way Galaxy, and contain trillions of stars in giant elliptical galaxies that can be several megaparsecs across. Elliptical galaxies typically exhibit little internal structure, with no spiral arms and no central bulge. They are designated in the Hubble classification by the letter *E* with the numbers 1–7 indicating a progression from least- to most-elongated varieties.

Elliptical galaxies also differ from spiral galaxies in that they contain little gas and dust, and they seem not to have any young stars or places where star formation is in the process of occurring (when the light was formed). Most of the stars in elliptical galaxies appear to be old, relatively cold, reddish low-mass stars, similar to the stars in the halo of the Milky Way and other spiral galaxies. Ellipticals are therefore old systems in which the gas and dust was all swept up by the star systems long ago, and the stars are moving about in irregular paths within the elliptical mass. As with most generalized statements, there are exceptions. Recent observations have shown that some giant elliptical galaxies have smaller areas that contain disks of gas and dust, but some astronomers speculate that these may be other spiral galaxies that collided with the giant ellipticals.

Hubble image of M51 Whirlpool Galaxy dated November 7, 2002 *(NASA Goddard Space Flight Center)*

Irregular galaxies include the whole range of other galaxies that do not fit into Hubble's spiral, barred spiral, or elliptical galaxy classes. These galaxies tend to lack systematic structure such as spiral arms or bulges, but they do contain large amounts of interstellar material such as dust and gas. Irr I type irregular galaxies slightly resemble distorted spiral galaxies, with famous examples including the Magellanic Clouds that orbit the Milky Way. The less common Irr II galaxies exhibit explosive or filamentous characteristics. Different models have been advanced to explain these characteristics of Irr II galaxies, including massive explosions inside the galaxies, or effects of close encounters with other galaxies. Most irregular galaxies contain between 1,000,000,000 to 100,000,000,000 stars, with the smaller "dwarf" irregular being more common than the larger elliptical galaxies.

PHYSICAL PROPERTIES OF GALAXIES

The observable universe presents an estimated minimum of 100 billion galaxies, and many of these have billions of stars in them. Most of these galaxies are located far from Earth and the Milky Way Galaxy, and thus are difficult to observe closely. To measure distances to and sizes of these distant galaxies one must use some objects, such as planetary nebulae or certain kinds of supernovae that have known brightnesses, and then use their apparent brightness to measure their distance from Earth. Another relationship that has been exploited to measure the distance to faraway galaxies is to measure their rotational speeds, and then correlate these with a known relationship between the rotational speed of a galaxy, its mass, and its luminosity. The rotational speed can be measured at great distances, and the absolute brightness calculated; then when compared with the apparent brightness, the distance to the galaxy can be calculated. Using these methods to measure distances to galaxies, scientists have found that most lie at vast distances from the Earth, most much greater than 20 megaparsecs away. Furthermore, there is some order to the large-scale structure in the arrangement of galaxies, with many residing in galaxy clusters, superclusters, and other even larger structures.

Determining the masses of distant galaxies can be difficult. For spiral galaxies within about 50 kiloparsecs of Earth, the rotational speed of the different spiral arms can be determined from the Doppler shifts of each arm, and if the distance from the galactic center is known, then Newton's laws of motion can be used to calculate the mass of a galaxy. For more distant galaxies one must depend on less reliable methods to estimate their masses. One way is to search for binary galaxy systems, then measurements of their orbital size and their orbital period enable the calculation of their mass using Kepler's third law. These different methods reveal that most spiral galaxies and large elliptical galaxies have about 10^{11}–10^{12} solar masses in them, while the irregular galaxies tend to be less massive, with 10^{8}–10^{10} solar masses. Dwarf ellipticals are the least massive, typically containing 10^{6}–10^{7} solar masses.

The rotational properties of most spiral galaxies and many elliptical galaxies indicates that they have excess mass surrounding them, but this mass is not luminous and is thought to be dark matter. The amount of dark matter in many cases is estimated to be 3–10 times the mass of the luminous matter in the galaxies. Galaxy clusters also appear to be associated with massive amounts of dark matter, with calculations showing that there must be between 10 and 100 times the masses of individual galaxy clusters. These calculations lead to the shocking conclusion that about 90 percent of the universe must be made up of invisible dark matter not detectable at any electromagnetic wavelength but can be observed only by its gravitational effects.

X-ray observations of galaxy clusters have demonstrated that some clusters are associated with strong emissions of X-ray radiation, and these are interpreted to be coming from hot gases that exist as intergalactic gas within the clusters. The mass of this gas is estimated, in some cases, to be about the same as or even more than the mass of the visible matter, but still substantially less than the mass needed to explain the gravitational observations by a factor of 10 to 100.

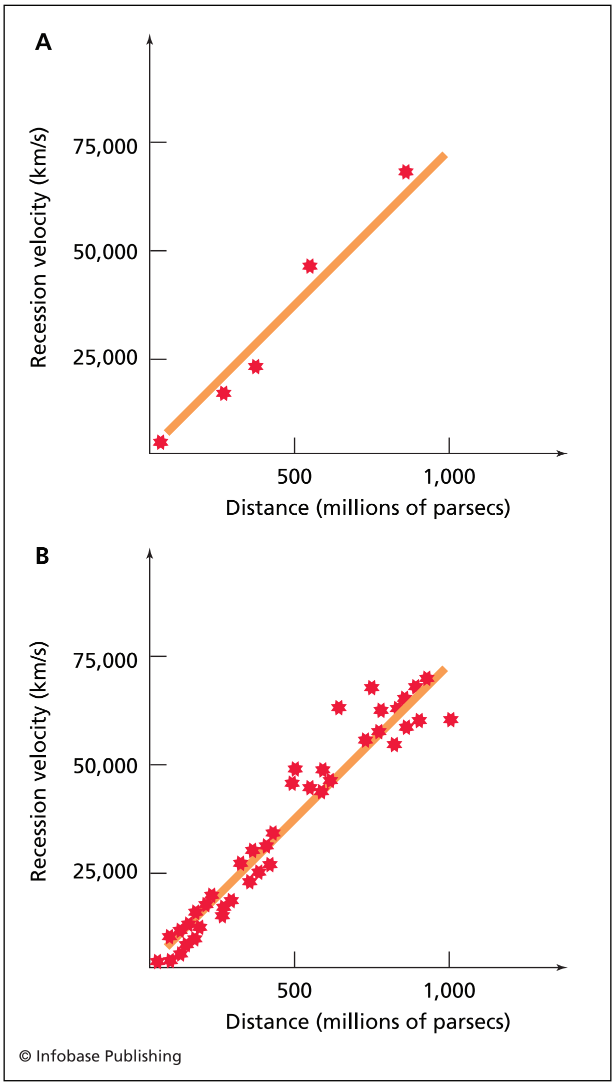
The motions of galaxies show interesting patterns on different scales of observation. The motion of individual galaxies within clusters of galaxies appears random, but the clusters show very ordered patterns to their motions at some of the largest scales of observation in the universe. Some of these motions have been partly understood for nearly a century. In 1912 Vesto Slipher, an American astronomer working with Percival Lowell (1855–1916), the American astronomer who founded Lowell Observatory and was president of Harvard University, discovered that every spiral galaxy he observed had a redshifted spectrum; Slipher concluded they were all moving away from the Earth. This observation has since been extended to include all known galaxies, which are moving away from the Earth in all directions. Individual galaxies not in clusters are moving away, as are the groups of galaxies in clusters, even though they have some random motions within the clusters. Furthermore, as observations improved, it became clear that the farther away the galaxy is from the Earth, the greater the redshift, and the faster it is receding.

In the 1920s the astronomer Edwin Hubble made a series of plots of the redshifts of galaxies and their calculated recessional velocities with distance from the Earth. He found that there is a straight-line relationship such that velocity increases steadily with distance. This proportionality is known as Hubble's law, and the general picture of all of the galaxies moving apart from one another is known as Hubble flow. Hubble's flow provides clear evidence that the universe is expanding.

Hubble's law can be written as follows:

$$V = H_0 \times D$$

where V is the recessional velocity, D is the distance, and H_0 is the proportionality constant (as Hubble's



Plot of recessional velocity versus distance for many galaxies within about 1 billion parsecs of Earth, illustrating Hubble's law, that recessional velocity is proportional to distance *(modified from Chaisson and MacMillan)*

constant) between the recessional velocity and distance. The slope of the straight line on a distance/recessional velocity diagram is equal to Hubble's constant, which turns out to be approximately 75 km/sec per megaparsec (46.5 miles/sec per 3.3 million light years). There is, however, uncertainty in the exact value of the Hubble constant, with nearly all estimates falling in the range of 37–56 miles per second (60–90 km/sec) per megaparsec. Hubble's constant represents the best estimate of the rate of expansion of the universe.

Hubble's law is also extremely useful for measuring distances to faraway objects. Since the recessional velocity is proportional to the distance of the object, it is simple to measure the recessional velocity (from the redshift of the spectrum), then use Hubble's law to estimate the distance directly. This method works well even for very distant objects and is used to calculate the distance to the most distant objects yet known in the universe—object QO51-279, which has a redshift showing a recessional velocity of 93 percent the speed of light, and a distance of 4,000 megaparsecs. The electromagnetic radiation now observable on Earth from QO51-279 was generated about 13 billion years ago, close to the time of the big bang (presently estimated to be 13.73 billion +/- 120 million years ago). Another extremely distant object was discovered in 2004 using the Hubble Space Telescope and an effect of general relativity called gravitational lensing, where massive objects in the foreground of a distant object can bend and magnify the light from the distant object, making it more observable. In 2004 a team of scientists discovered an object magnified by a gravitational lens in a galactic cluster (Abell 2218), and that object is a small, compact system of stars approximately 2,000 light years across and about 13 billion light years away. Using the present estimate of the age of the universe, scientists estimate the light from this object now reaching Earth was generated when the universe was only 750 million years old.

Using powerful telescopes and Hubble's law, scientists can now map the large-scale structure of the universe. It turns out that the universe is not a random collection of star and galaxy systems but rather a patterned distribution of galaxies and clusters of galaxies, which are arranged in a network of string- or filament-like groups, separated by largely empty space known as voids. Astronomers have mapped these stringlike features to be on the surfaces of bubblelike voids, as if the universe were made of a system of empty bubbles with galaxy clusters forming chains along the surfaces of the bubbles. The areas where several bubbles intersect tend to be where the densest galaxy clusters and superclusters are located. The origin of these bubblelike structures is debated but must be related to density fluctuations or ripples in the earliest stages of the formation of the universe that grew during time and the expansion of the universe.

GALACTIC EVOLUTION

Despite years of research, there is still remarkably little known about the processes of galaxy formation and why there is such variety in the structure of different galaxies. Most astronomers suggest that small density fluctuations in the primordial matter led to the formation of many small "pregalactic masses" that were similar to present-day dwarf galaxies, and that collisions and mergers of these galaxies led to the formation of the larger galaxies common in the present universe. As the universe expanded, these merged galaxies grew into the large-scale clusters and voids that now occupy the universe. Much of the evidence for such a history of galaxy formation comes from observations of the most distant objects in the universe, whose light and other electromagnetic radiation that reaches Earth now was generated billions of years ago when the universe was young. It seems that the further back in time one observes, the smaller and less organized individual galaxies appear. Furthermore, there are many examples of galaxies merging, and many stages are observed of irregular galaxies merging to form more complex systems.

Different ideas and models attempt to explain why some galaxies are elliptical, some spiral, and some irregular. This variation may relate to the timing of when the stars in the galaxy formed compared to the galactic formation—if the stars formed early in the galactic evolution, an elliptical galaxy would most likely form, since the gas would be used up, and no central disk would form. In these elliptical galaxies star formation would occur early, and their present state would be dominated by systems with relatively old and cold stars. In contrast, if a lot of gas remained in the galaxy after it formed, then gravity would make this gas tend to collapse into a rotating disk, forming spiral galaxies, with stars able to form throughout the history of these types of galaxies.

The reason why some galaxies may have early star formation and form ellipticals, whereas others have late star formation and form spirals, is still not clearly known. But it is known that spiral galaxies are comparatively rare in parts of the universe that have high galactic density, perhaps because collisions between galaxies are more common in areas of high galactic density, and collisions tend to destroy the spiral arm structures of these galaxies. Observations and computer models suggest that collisions between galaxies tend to leave new galaxies that have elliptical characteristics, and these collisions eject large amounts of gas into intergalactic space. Also observations of deep space show that ellipticals were more common earlier in the universe, and are becoming less common with time, suggesting that collisions may be destroying their spiral structure with time.

Although many galaxies formed early in the history of the universe, many are still forming or being extensively modified through collisions and other interactions that are ongoing in the present-day universe. As galaxies interact, their halos of dark matter first interact and may be transferred from one (relatively smaller) galaxy to another, then the galaxies may spin in toward each other and merge, typically with the larger galaxy absorbing (or cannibalizing) the smaller. Other computer models of interactions between galaxies show that it is possible for galaxies to come close but not merge, and one possible outcome of these types of interactions is the formation of spiral arms in one galaxy, where none existed before. Other interactions between galaxies produce sudden bursts of new star formation in the affected galaxies, showing that galaxy and stellar formation is an ongoing process in the universe.

See also ASTRONOMY; ASTROPHYSICS; COSMOLOGY; DARK MATTER; GALAXY CLUSTERS; HUBBLE, EDWIN; KEPLER, JOHANNES.

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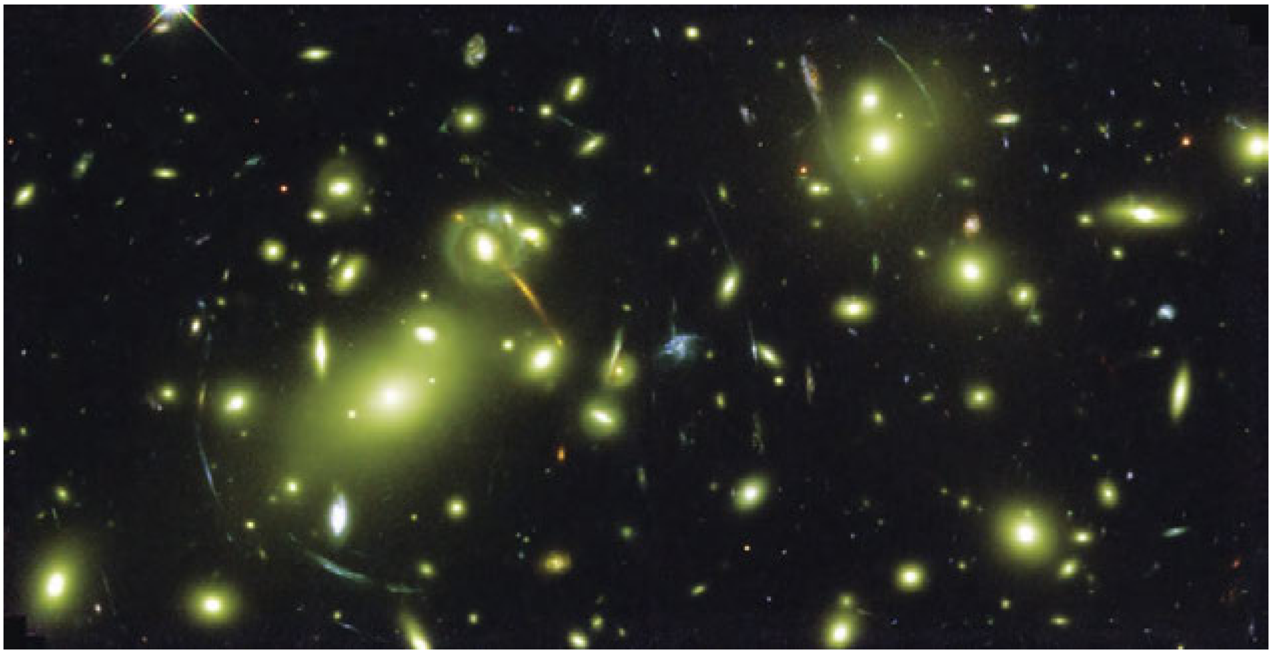
galaxy clusters Most galaxies lie at great distances from the Earth and the Milky Way Galaxy, and tend to form groups or clusters held together by their mutual gravitational attraction. These groups or clusters are separated by voids characterized by relatively empty space apparently devoid of luminous matter. The Milky Way Galaxy is part of the Local Group, which also includes the large Andromeda Spiral galaxy, the Large and Small Magellanic Clouds, and about 20 smaller galaxies. Most of the galaxies in the Local Group are elliptical and dwarf irregular systems, and the diameter of the local group is about 1 megaparsec.

Several types of galaxy clusters exist. Regular clusters are spherical with a dense central core, and are classified based on how many galaxies reside within 1.5 megaparsecs of the cluster center. Most regular clusters have a radius of 1–10 megaparsecs and masses of 10^{15} solar masses. In some cases such as the Coma cluster, there may be thousands of galaxies within 1.5 megaparsecs of the center of the cluster, making this one of the densest large-scale regions in the universe.

Irregular clusters generally have slightly lower mass (~10^{12}–10^{14} solar masses) than regular clusters



Cluster of galaxies called Abell 2218, taken by *Hubble Space Telescope* *(NASA, A. Fruchter and the ERO Team, STScI, ST-ECF)*

and have no well-defined center. An example of an irregular cluster is the Virgo cluster.

Galaxies and galaxy clusters are further grouped into even larger structures. Superclusters typically consist of groups or chains of clusters with masses of about 10^{16} solar masses. The Milky Way Galaxy is part of one supercluster, centered on the Virgo cluster, and has a size of about 15 megaparsecs. In contrast, the largest known superclusters, like that associated with the Coma cluster, are about 100 megaparsecs across. Recent advances in astronomers' ability to map the distribution of matter in space reveal that about 90 percent of all galaxies are located within a network of superclusters that permeates the known universe.

The largest-scale structures known in the universe include an understanding that these galaxy clusters and superclusters form a bubbly type of distribution of galaxies and clusters, with voids that are about 25 megaparsecs across separating sheets and filaments of galaxy clusters. The Great Wall is one such structure—a sheet of galaxies about 100 megaparsecs long, located about 100 megaparsecs from Earth.

Studies of the redshifts of galaxies from Earth reveal that many groups of galaxies on scales of 60 megaparsecs across are moving in a relatively coherent way, as if they are linked by some large-scale structure. Consistent with this idea is the determination that the Milky Way Galaxy, along with our local group, is moving at about 600 km/sec toward an area in space about 45 megaparsecs away in the Centaurus Supercluster, known as the Great Attractor. The mass in this area is calculated to be in excess of 5 X 10^{16} solar masses, and is likely a diffuse concentration of matter about 400 million light years across, perhaps a supercluster itself.

See also ASTRONOMY; ASTROPHYSICS; COSMOLOGY; GALAXIES.

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Galilei, Galileo (1564–1642) Italian *Physicist, Mathematician, Astronomer* Galileo, born on February 15, 1564, in Pisa, Italy, played a major role in the scientific revolution during his life. His main contributions include making dramatic improvements in the telescope and using this as a tool to explore the heavens, providing support for the Copernican heliocentric model for the universe. He worked on the equations of motion for uniformly accelerated bodies and contributed to the science of kinematics, the study of the motion of objects. He became famous for his observations of Venus and sunspots. His views on heliocentrism were opposed by the Roman Catholic Church, which caused him to spend his final years under house arrest. The Church kept this position until 1981, when Pope John Paul II urged the Pontifican Academy of Sciences to reconsider Galileo's case and formed the Galileo Commission. In 1992, after more than a decade of investigation, the commission reversed the Church's earlier conviction of heresy and reversed its earlier verdict, finding Galileo not guilty of heresy. A statue was erected to honor Galileo in the Vatican gardens in 2009 on the 400th anniversary of his invention of the telescope.

PERSONAL LIFE

On February 15, 1564, Galileo Bonaiuti de'Galilei was born as the first of six children of Giulia Ammannati and Vincenzo Galilei, a famous lute player and music theorist of his time. When he was eight his family moved to Florence, and Galileo eventually enrolled at the University of Pisa to pursue a medical degree. During his studies Galileo changed to mathematics, and in 1589 at the age of 25 he was appointed as chair of mathematics at the university. In 1592 he moved to the University of Padua—one of the oldest in Italy, founded in 1222—where he taught geometry, mechanics, and astronomy until 1610. During this interval Galileo made major discoveries in the kinematics of motion, astronomy, and the strength of materials, and made improvements in the telescope.

Galileo had three children with Marina Gamba, but they were not married so their daughters (Virginia and Livia) were considered unmarriageable and spent their lives in the Convent of San Matteo in Arcetri. Their son, Vincenzio, was legitimized by the church and married Sestila Bocchineri.

In 1610 Galileo published a remarkable account of his observations of the moons of Jupiter and used this to argue for a Sun-centered (Copernican) model for the universe. In 1611 he went to Rome to show his telescope and the moons of Jupiter to leading philosophers at the Jesuit Collegio Romano, and at this time he was made a member of the Accademia dei Lincei.

In 1612 Father Tommaso Caccini denounced Galileo's models and ideas as being close to heresy, and when Galileo went to Rome in 1616 to defend his observations, Cardinal Roberto Bellamino admonished him and ordered him to stop teaching and advocating Copernican astronomy. In 1630 he applied in Rome for a license to print his book, *The Dialogue Concerning the Two Chief World Systems,* which was published in Florence in 1632, but he was ordered instead to appear in the office of the church in Rome. The church put Galileo on trial for heresy, and from that time on, the pope ordered him to remain under house arrest in his country house in Arceti (near Florence). Galileo went blind in 1638 after suffering from insomnia and a hernia. After suffering additional fever and heart palpitations in 1642, he died at the age of 78.

SCIENTIFIC CONTRIBUTIONS

Galileo was one of the first scientists to state clearly that the laws of nature could be explained mathematically. In his book *The Assayer,* published in Rome in 1623, Galileo wrote that "the universe is written in the language of mathematics, and its characters are triangles, circles, and other geometric figures." Galileo was driven by testing assertions by scientists, philosophers, and religious figures through experimentation and mathematics, and this passion and reason in his character led him to reject many positions of authority, especially in the church. He became a major proponent of the need to separate religion and science. Galileo was instrumental in deriving mathematical relationships between curves, the equations to describe the curves, and relating these to the physical world. For instance, he noted that the parabola describes the path of a projectile moving without the effects of friction, and derived equations to explain this motion. He created standards for length and time to be used in laboratory experiments, so that results from different labs and different days could be compared. Many later scientists including German-American physicist Albert Einstein and British physicist Stephen Hawking have suggested that Galileo should be considered the father of modern science.

Galileo is widely credited with inventing the telescope. This invention was based on crude descriptions of a similar device from the Netherlands in 1608. By 1609 Galileo had made a telescope with the ability to magnify objects threefold (3×), soon improving this to a magnification of 30×. He immediately applied this device to study the stars, publishing a short note of his astronomical observations entitled *Sidereus Nuncius* (starry messenger) in March 1610. On January 7, 1610, Galileo observed "three fixed stars, totally invisible by their smallness, all within a short distance of Jupiter, and lying on a straight line through it." On the following nights he determined that these so-called fixed stars were moving in unusual ways that showed they could not be stars, and on January 10 he noted that one of them had disappeared by moving to a position behind Jupiter. A few days later Galileo concluded that he had discovered objects (moons) orbiting Jupiter, and he named them Medicean stars in honor of his patron Cosimo II de'Medici, the grand duke of Tuscany. These moons were later renamed the Galilean satellites (after Galileo), and included Io, Europa, and Callisto. Galileo discovered a fourth moon, Ganymede, on January 13.

Galileo's discovery of moons, or small planets circling another planet, was in direct contradiction to the cosmology of Aristotle and the teachings of the Catholic Church, that all heavenly bodies circle the Earth. Many scholars and theologians were therefore opposed to Galileo's discovery, and many claimed it must be false.

Galileo made more discoveries, including observations that Venus exhibited phases in a manner similar to that of the Moon. He explained this using Copernicus's heliocentric model of the solar system and presented mathematical arguments that if the Earth was the center of the solar system as in the Aristotelian view, then only the crescent phases of Venus would be visible. His observations proved that Venus orbited the Sun and played a major role in convincing the scientific community in the 1600s that the solar system was not purely geocentric. This would stand as one of Galileo's most important contributions to science.

Galileo's observations of Saturn and sunspots also showed changes in both of these heavenly bodies that were making a substantial change in scholars' thoughts about the universe. In contrast to the Aristotelian view of a nonchanging universe, Galileo demonstrated that the universe was dynamic and always changing. This remains one of Galileo's major lasting contributions to science.

Using his telescopes, Galileo Galilei also became the first to describe craters and mountains on the Moon. Using measurements of the lengths of shadows and his skills with trigonometry, Galileo even estimated the heights of these mountains. Using his telescope, Galileo deduced that the Milky Way was not nebulous as previously thought, but actually consisted of a vast number of stars that were so densely concentrated that they appeared nebulous from the Earth when viewed with the naked eye.

In addition to his contributions to pure science Galileo made many contributions to technology. The first of these (1595–98) in his repertoire was a geometric and military compass for surveyors and gunners. It was a remarkable instrument for its time, capable of helping to construct and calculate the area of any polygon or circular section, and for gunners it was helpful to calculate the angle and amount of powder needed to fire cannonballs of different weights to their intended targets. In 1593 Galileo designed and built a thermometer that used the expansion and contraction of an air bubble by heat to move a column of water in a calibrated tube. Galileo's most famous contribution to technology was his construction in 1609 of a refracting telescope that he used to explore the heavens. The following year he turned the telescope earthward and modified the optics so that he could magnify insects, and by 1624 he had perfected the first compound microscope, used the following year to publish his detailed observations of insects. Some of Galileo's inventions turned out to be not so popular, such as his automatic tomato picker, his combination pocket comb and eating utensil, and an early version of a ballpoint pen.

Galileo also contributed significantly to physics and mathematics. Folklore (possibly apocryphal) has it that Galileo demonstrated his ideas of classical mechanics by dropping balls of the same material, but with different masses, from the Leaning Tower of Piza, demonstrating that their rate of descent was not dependent on mass. This was contrary to the ideas of Aristotle, who said that heavier objects fell faster than lighter ones, an idea easily disproved. Galileo appreciated the effects of friction, and suggested that falling bodies would fall with a uniform acceleration as long as the resistance to motion was negligible. Galileo was also the first to state that moving objects retain their velocity unless acted on by an external force, such as friction. This too contradicted Aristotelian physics, which claimed that objects naturally slowed down unless acted on by a force to keep them moving, although this idea had been proposed many centuries earlier by Chinese philosopher Mozi (Mo Tzu, 470–391 B.C.E.). Galileo's principle of inertia specifically stated that "a body moving on a level surface will continue in the same direction at constant speed unless disturbed," an idea later incorporated into Newton's first law of motion. In another prescient tome, Galileo advanced his basic principle of relativity, in which he stated that the laws of physics are the same in any system moving at a constant velocity, regardless of the speed or direction. This principle formed the early basis for Einstein's special theory of relativity.

See also ASTRONOMY; ASTROPHYSICS; BRAHE, TYCHO; COPERNICUS, NICOLAUS; EINSTEIN, ALBERT; IMPACT CRATER STRUCTURES; JUPITER; VENUS.

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Gamow, George **(1904–1968) Russian Empire (Ukrainian)** ***Theoretical Physicist and Cosmologist*** George Gamow was born Georgiy Antonovich Gamov in Odessa, Russian Empire, on March 4, 1904, and was educated at the Novorossiya University in Odessa from 1922 to 1923, and at the University of Leningrad from 1923 to 1929. He is best known for his prediction of the cosmic microwave background radiation, as well as work on the big bang theory and on alpha decay by quantum tunneling.

Gamow's career began after his work on quantum theory landed him a job at the Theoretical Physics Institute at the University of Copenhagen in 1928. He visited other laboratories to collaborate with other leading physicists of the time, including the British physicist Ernest Rutherford, considered the father of nuclear physics. His work at this point included solving a complex problem in radioactivity, in which he described how alpha decay of an atomic nucleus happens when a high-energy particle can tunnel through and escape the high-energy field that keeps the atomic nucleus together, with a specific half-life that is dependent on the type of nucleus. With increasing oppression in Russia, Gamow and his wife, Lyubov Vokhminzeva, attempted to leave the country twice in perilous sea voyages by kayak that both ended in failure because of bad weather. The couple managed to escape in 1933 by getting permission to attend a conference, then defecting to the United States, where they became naturalized citizens in 1940.

Gamow worked in cosmogony, the study of the origin of the universe, publishing a landmark paper in 1948 in the journal *Physical Review* called "The Origin of the Chemical Elements," suggesting that the present abundance of hydrogen and helium in the universe was acquired by reactions in the big bang. In the paper Gamow and his colleagues (one of whom was fictional) predicted the strength of the residual cosmic microwave background radiation that should be left over as an afterglow from the big bang, even though no such radiation had at that time been detected. This radiation was not detected until 16 years later, when Arno Penzias and Robert Wilson of Bell Laboratories in New Jersey detected the cosmic background radiation (earning them the Nobel Prize in physics in 1878) at 2.7 degrees above absolute zero, a couple of degrees lower than Gamow's prediction of 5 Kelvin made in 1948.

See also ASTRONOMY; ASTROPHYSICS; COSMOLOGY.

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geochemical cycles *Geochemical cycles* refers to the transportation, cycling, and transformation of the different chemical elements through various reservoirs or spheres in the Earth system, including the atmosphere, lithosphere, hydrosphere, and biosphere. The cycles occur through a great variety of processes, timescales, and different reservoirs or systems within the whole Earth system. Geochemical cycles are characterized by a closed flow in the Earth system; if the system is fully defined, the particular element remains in the same abundance in the cycle but moves from location to location by a series of processes. In other words, there is a material balance in geochemical cycles. The most basic picture of a geochemical cycle is analogous to the rock cycle, where molten magma rises from the deep interior of the Earth, crystallizes to form an igneous rock, then erodes to form a sedimentary rock, which gets buried and becomes a metamorphic rock, which eventually is heated to become a magma that rises back to the surface.

All geochemical cycles have a characteristic time necessary for completion. The longest is the geochemical cycle that brings material from deep within the Earth to form midocean ridges that then form oceanic crust that gets subducted, returned to the deep mantle to eventually rise back to the surface. This cycle takes from several hundred million years to about 4.5 billion years by some estimates.

The material balance of chemical elements in a geochemical cycle can be complex and includes transfer of the element between many different geological, biological, atmospheric, and liquid systems. The cycles are largely controlled by and can act as indicators of past conditions of other factors such as the configuration and elevation of the continents, distribution of landmasses and vegetation, large volcanic eruptions, climate, and biological production. Geochemical cycles are generally divided into two types, those that occur near the Earth's surface (exogenic cycles) and those that occur in the deep interior (endogenic cycles).

WATER CYCLE

The global water cycle is one of the major drivers and reservoirs for other geochemical cycles on the Earth. The water cycle describes the sum of processes operative in the hydrosphere, a dynamic mass of liquid continuously on the move between the different reservoirs on land and in the oceans and atmosphere. The hydrosphere includes all the water in oceans, lakes, streams, glaciers, atmosphere, and groundwater, although most water is in the oceans. The hydrologic, or water, cycle encompasses all of the changes, both long- and short-term, in the Earth's hydrosphere. Heat from the Sun powers the hydrologic cycle, causing water to change its state through evaporation and transpiration. Water is both a means of transport for other chemical components and a reactive agent that removes these other elements from rocks and soils on the continents and moves them into other reservoirs in the oceans.

The water cycle can be thought of as beginning in the ocean, where energy from the Sun causes surface waters to evaporate, changing from the liquid to the gaseous states. Evaporation takes heat from the ocean and transfers this heat into the atmosphere. An estimated 102 cubic miles (425 cubic km^3) of water evaporate from the ocean each year, leaving the salts behind in the ocean. The water vapor then condenses into water droplets in clouds and eventually falls back to the Earth as precipitation. Most (92 cubic miles; 383 cubic km^3) falls directly back into the ocean, but about 26 cubic miles (108 km^3) of precipitation falls as rain or snow on the continents, transforming salty water of the oceans into freshwater on the land. Nearly three-fourths of this water (17 cubic miles, or 71 cubic km/yr) evaporates back to the atmosphere or is aided by the transpiration from plants, returning the water back to the atmosphere. The other estimated 10 cubic miles (42 km^3) per year of water runs across the surface, some merging together to form streams and rivers that flow eventually back into the ocean, and other parts seeping into the ground to recharge the groundwater system. Humans now intercept approximately half of the fresh surface water for drinking, agriculture, and other uses and make a significant impact on the natural hydrological cycle. Water that seeps into the groundwater system is said to infiltrate, whereas water that flows across the surface is called runoff.

Water in the atmosphere is one of the major greenhouse gases that help to regulate global temperature and climate. Changes in the water content in the atmosphere can change the erosion rate of different chemical elements on land, the evaporation rate from the ocean, and the balance between many other geochemical cycles.

SODIUM CYCLE

One of the most important geochemical cycles is the sodium cycle. Sodium is one of the major constituents of crustal rocks, sediments, and ocean water, and moves from each of these reservoirs to the other over long geological times. Sodium is dissolved from crustal rocks such as granite by rainwater, then streams and rivers carry it in solution to the sea. Sodium (Na) and chlorine (Cl) are the two most abundant elements carried in solution in ocean water. They combine to form the mineral halite (NaCl) that remains following evaporation of sea water. The conversion from dissolved sodium to sodium in the mineral halite is ongoing in many areas of strong evaporation along seashores around the world. At times in the geological past large sections of ocean basins (the Mediterranean Sea, Red Sea, juvenile Atlantic Ocean) have evaporated, leaving thick deposits of salts. Stream waters re-erode some of these deposits and carry them back to the sea, completing one circuit of the geochemical cycle.

When the salt deposits get buried on the seafloor the salt may be interlayered with oceanic muds, then the sodium is removed from the salts and transferred into clay minerals. Replenishing the amount of sodium in the ocean by river flow from the continents takes an estimated 65–100 million years. If the concentration of sodium (or other element in other geochemical cycle) remains the same in one reservoir such as the ocean basins, over time, then there is a balance between the input of that element to the system and its extraction to other systems. The amount of time it takes to replenish that amount reflects this balance, and is known as the residence time, obtained by dividing the mass of the element in the reservoir by the rate of input to the system.

Sodium in the seafloor sedimentary deposits can react with the basalt of the ocean crust, forming veins, and can replace other elements in the basalt. Ultimately these basalts and sediments containing sodium get subducted into the mantle, where some remelt to form igneous rocks that rise to the surface, containing minerals with sodium. These then are prone to erosion by rivers, leaching away sodium to be carried back to the ocean. Other atoms of sodium are carried deeper into the mantle, forming the longest residence time arm of the sodium cycle.

CARBON CYCLE

The carbon cycle preserves a record of many processes on the Earth throughout the planet's history and includes many geologic, biologic, ocean, and atmospheric systems. Many volatile substances including water and carbon dioxide were degassed from the deep interior of the Earth during the early Archean, and some has been added by cometary and meteorite impact. The early atmosphere of the Earth was rich in carbon dioxide (CO_2), and since the Archean this CO_2 has been progressively removed by the precipitation of limestones (with a composition close to $CaCO_3$), and by photosynthesis that converts the CO_2 (along with nitrogen, phosphorus, and sulfur) into organic matter, releasing free oxygen in the process. The development of life on the Earth enhanced the formation of limestones and other carbonates, since many organisms secrete calcium carbonate for their shells and tissues. Inorganic processes since the Archean formed other limestones.

Over long geologic times carbon dioxide returns to the atmosphere by decomposition of limestones subducted to the Earth's deep interior, releasing carbon dioxide through gases dissolved in magmas that rise to the surface. Plate tectonics and the supercontinent cycle also play a large role in cycling carbon between the atmosphere and rock sphere. When many continents collide to form a supercontinent, the passive margins on these continents that contain thick limestone sequences are uplifted above sea level. The tectonic uplifting of carbonate rocks causes them to be exposed to the atmosphere during continental collisions. The calcium carbonate ($CaCO_3$) then combines with atmospheric CO_2, depositing it in the oceans. Thus continental collisions and times of supercontinent formation are associated with drawdown and reduction of CO_2 from the atmosphere, global cooling, and sea-level changes.

The mass of carbon stored in the limestone and organic matter reservoirs on Earth is huge, about 2,000 times greater than all the carbon presently in the atmosphere and oceans combined. Living plants contain about the same amount of carbon as that in the atmosphere, so human activities such as deforestation that change the vegetation balance on the planet may significantly change the balance between atmospheric and living organic reservoirs for the carbon, putting more CO_2 in the atmosphere and altering global climate.

Living plants take CO_2 out of the atmosphere and release one molecule of oxygen for every molecule of carbon dioxide used to make organic matter. When these plants die, much of the organic matter is oxidized and returned into CO_2, but some escapes this process and becomes buried in organic sediments in another reservoir to store carbon. There is a delicate balance between the carbon cycle and the oxygen cycle, as the amount of oxygen released indicated by the mass of the present-day mass of the organic carbon reservoir is 30 times the present atmospheric level, so there is recycling of both carbon and oxygen on geological timescales. Similar relationships exist among biological, geological, and atmospheric processes for the geochemical cycles of nitrogen, phosphorus, and sulfur. Plants absorb these elements in fixed proportions from different environments, store them in organic soils, where groundwater can leach these elements into the hydrological system, bringing them to the ocean, where they form building blocks for new life.

See also ASTHENOSPHERE; ATMOSPHERE; BIOSPHERE; CARBON CYCLE; CLIMATE CHANGE; CONVECTION AND THE EARTH'S MANTLE; ENERGY IN THE EARTH SYSTEM; GAIA HYPOTHESIS; GREENHOUSE EFFECT; HYDROSPHERE; LITHOSPHERE; MAGMA; PASSIVE MARGIN; PHOTOSYNTHESIS; PRECAMBRIAN; SUBDUCTION, SUBDUCTION ZONE; SUPERCONTINENT CYCLES; WEATHERING.

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geochemistry Geochemistry is the study of the distribution and amounts of elements in minerals, rocks, ore bodies, rock units, soils, the Earth, atmosphere, and by some accounts, other celestial bodies, and the principles that govern the distribution and migration of these elements. This field of earth science includes the study and analysis of the movement of chemical elements, the properties of minerals as related to their distribution and concentrations of specific elements, and the classification of rocks based on chemical composition.

The field of geochemistry began with the discovery of 31 chemical elements by the French chemist Antoine Lavoisier in 1789, with the first mention of the word by German chemist Christian F. Shonbein in 1813. In 1884 the United States Geological Survey (USGS) established a laboratory to investigate the chemistry of the planet and appointed F. W. Clarke as head of the laboratory. Since then the USGS has been one of the world's leaders in the collection and analysis of geochemical data. In 1904 the Carnegie

Institution in Washington, D.C., established the Geophysical Laboratory, which tests physical and chemical properties of minerals and rocks. The Vernadsky Institute in Moscow, Russia, had a similar charge, and both institutions spearheaded a revolution in technologies applied to analyzing the composition of rock materials, leading to the proposition of the concepts of chemical equilibrium, disequilibrium, and amassing of huge databases encompassing the chemistry of rocks of the world. Geochemist Victor M. Goldschmidt from the University of Oslo, Norway, applied the phase rule, explaining metamorphic changes in terms of chemical equilibrium.

Geochemistry is commonly studied by using several different methods:

- chemical analysis, in which rocks are broken down into major and minor (trace) constituents and measured in the laboratory
- analysis of the atomic and chemical structure, physical properties of minerals, and properties of rocks as reflected in their geochemistry
- direct experimentation, under controlled conditions. In experimental geochemistry controlled conditions are created to simulate processes of formation of various materials, and phase relations between the materials are determined.
- study of the dispersion and accumulation of elements under dynamic conditions

Geochemistry is subdivided into several fields:

- isotope geochemistry, which involves the measurement of the concentration of elements and their isotopes in different Earth and planetary systems, uses stable and radiogenic isotopes to understand different mineral and rock systems, and dates geological events using radioactive decay of isotopes
- geochemical cycling, which uses the changes in the distribution of elements in different parts of the Earth to understand these different mineral, rock, water, and biological systems
- cosmochemistry, which analyses the distribution of elements and their isotopes in space
- biogeochemistry, which assesses the role of life and organisms on the chemistry of the Earth and earth systems
- organic geochemistry, which examines the role of processes and compounds by living and once-living organisms
- environmental and exploration geochemistry, including applications of chemistry to environmental, hydrological, and mineral exploration studies

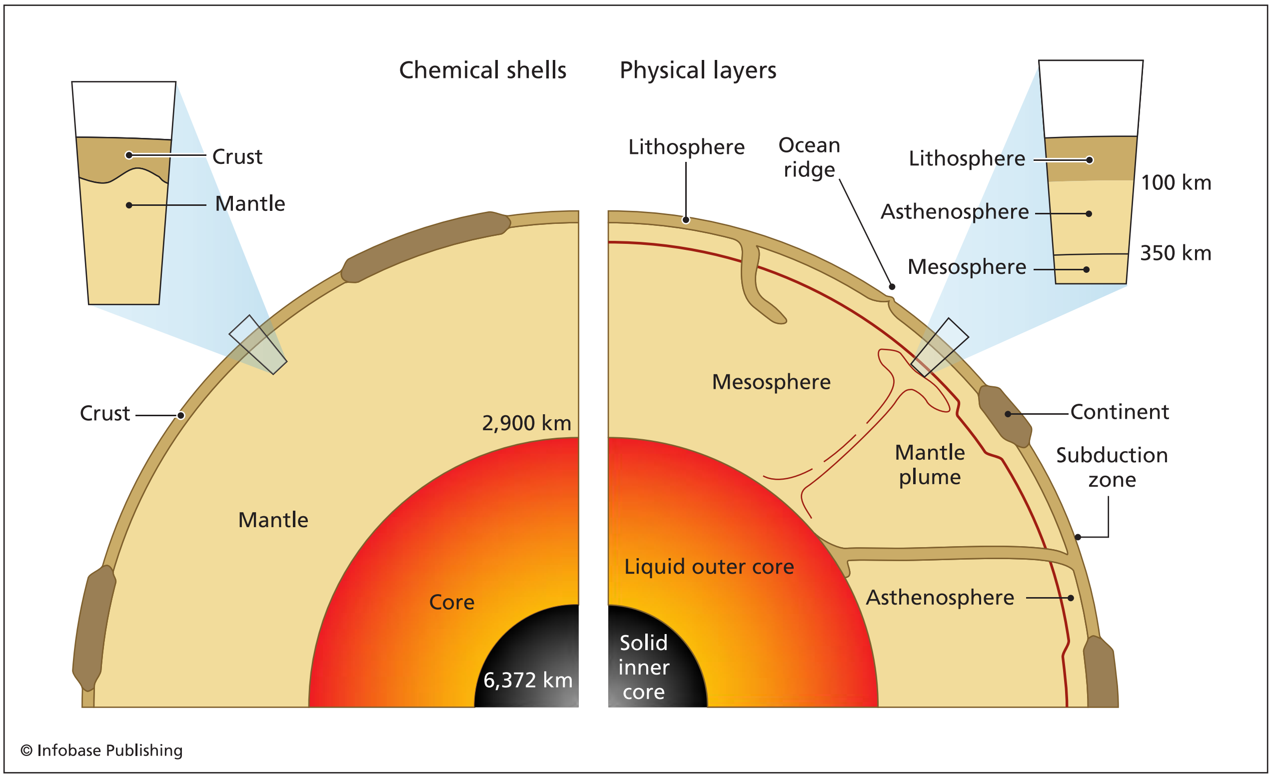
GEOCHEMISTRY AND THE COMPOSITION OF THE EARTH

Geochemists have worked closely with cosmologists to obtain a better understanding of the chemical composition of the universe and Earth-Moon system in the field of cosmochemistry. These cosmochemists have produced models for how the chemical composition of the universe began, initially consisting almost exclusively of hydrogen and helium, and evolved through stellar processes and supernovas to include heavier elements. Studies of meteorites have yielded data on the average composition of the rocky planets in the inner solar system, and these data have been used to derive a model for the average composition of the Earth. The Earth is thought to have an overall composition close to that of a carbonaceous chondrite meteorite. The planet experienced early heating due to the decay of short-lived radioactive isotopes and heat from gravitational compaction and the collection in the core of metallic phases that sink and release heat. This early heating formed a melt phase within the Earth, and the outer core is still molten, as shown by seismic waves. This causes a chemical and density zonation in the Earth.

The chemical and density zonation has broken the Earth into several different shells with different properties. These layers include the crust, upper mantle, transition zone, lower mantle, outer core, and inner core. The Earth's magnetic field is formed by motions in the liquid outer core, where a dynamo effect generates a magnetic field by the motion of electrically charged fluid. The lower mantle has a composition that includes magnesium and iron silicate concentrations, similar to chondritic meteorites.

There are a couple of major polymorphic transitions within the Earth that are of great importance for determining overall Earth structure and behavior. At 250 miles (400 km) depth pyroxene minerals attain a garnet structure by the increase in pressure from higher in the Earth, but they maintain a pyroxene composition. Also the crystal lattice structure of olivine—one of the most abundant elements in the mantle—changes from an olivine to a denser crystal lattice structure known as a spinel structure at the same depth. Deeper, at 435 miles (700 km), the garnet and spinel structures react together and change into progressively denser crystal lattices including ilmenite, then to a perovskite structure, still retaining the olivine and pyroxene composition, although possibly with more iron present.

Geochemists have determined that the Earth is not yet completely chemically fractionated. Volcanoes continue to release gases such as sulfur and carbon dioxide, and deep eruptions such as those



Cross sections of the Earth showing chemical shells (crust, mantle, and core) and physical layers (lithosphere, asthenosphere, mesosphere, outer core, and inner core)

through kimberlites have recently released diamonds, showing that there is still carbon at depth. Carbon dioxide is presently being degassed from the interior of the Earth at high rates, showing that fractionation is an ongoing process. The composition of the Earth and its different layers has been calculated based on density measurements, gravity, deep samples erupted from volcanoes, and models based on the composition of meteorites. The crust has been calculated by geochemists to have a composition that is about:

- 47 percent oxygen (O)
- 28 percent silicon (Si)
- 11 percent iron (Fe), magnesium (Mg), and calcium (Ca)
- 8 percent aluminum (Al)
- 6 percent potassium (K), sodium (Na), and all other elements

In terms of minerals in the Earth's crust this equates with about

- 49 percent feldspar
- 21 percent quartz
- 5 percent pyroboles (includes pyroxene, amphibole, and olivine)
- 8 percent micas
- 7 percent magnetite and all other minerals

The overall distribution of elements in the whole Earth is quite different and resembles a massively differentiate giant meteorite with a crust on top. The whole Earth has a composition that has

- 38 percent of the mass in the core divided between 35 percent iron (Fe) and 2.7 percent nickel (Ni)
- 28 percent oxygen, distributed mostly in the mantle
- 17 percent magnesium (Mg)
- 13 percent silicon (Si)
- 2.7 percent sulfur (S)

See also ASTROPHYSICS; COSMOLOGY; EARTH; IGNEOUS ROCKS; ORIGIN AND EVOLUTION OF THE EARTH AND SOLAR SYSTEM; METEOR, METEORITE; MINERAL, MINERALOGY, MINERALS; STELLAR EVOLUTION.

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geochronology Geochronology is the study of time with respect to Earth history, and includes both absolute and relative dating systems as well as correlation methods. Absolute dating systems include a variety of geochronometers such as radioactive decay series in specific isotopic systems that yield a numerical value for the age of a sample. Relative dating schemes include cross-cutting features, and discontinuities such as igneous dikes and unconformities, with the younger units being the cross-cutting features or those overlying the unconformity.

During the 19th and early 20th centuries geochronologic techniques were crude. Many ages were estimated by the supposed rate of deposition of rocks, and correlation of units with unconformities with other, more complete sequences. With the development of radioactive dating it became possible to refine precise or absolute ages for specific rock units. Radiometric dating operates on the principle that certain atoms and isotopes are unstable. These unstable atoms tend to decay into stable ones by emitting a particle or several particles. Alpha particles have a positive charge and consist of two protons and two neutrons. Beta particles are physically equivalent to electrons or positrons. These emissions are known as radioactivity. Half-life is the time it takes for half of a given amount of a radioactive element to decay to a stable element. By matching the proportion of original unstable isotope to stable decay product, and knowing the half-life of that element, one can thus deduce the age of the rock. The precise ratios of parent-to-daughter isotopes are measured by a mass spectrometer.

William F. Libby (1908–80) developed radiocarbon, or carbon 14, dating techniques at the University of Chicago in 1946. This major breakthrough in dating organic materials is now widely used by archaeologists, Quaternary geologists, oceanographers, hydrologists, atmospheric scientists, and paleoclimatologists. Cosmic rays entering Earth's atmosphere transform regular carbon (carbon 12) to radioactive carbon (carbon 14). Within about 12 minutes of being struck by cosmic rays in the upper atmosphere, the carbon 14 combines with oxygen to become carbon dioxide that has carbon 14. The radioactive carbon dioxide diffuses through the atmosphere and is absorbed by vegetation (plants need carbon dioxide to make sugar by photosynthesis). Every living thing contains carbon. While it is alive, each plant or animal exchanges carbon dioxide with the air. Animals also feed on vegetation and absorb its carbon dioxide. At death the animal no longer exchanges carbon 14 with the atmosphere, but the radioactive element continues to decay within the organic material. Theoretically analysis of this carbon 14 can reveal the date when the object once lived by the percent of carbon 14 atoms still remaining in the object. The radiocarbon method has subsequently evolved into one of the most powerful techniques to date late Pleistocene and Holocene artifacts and geologic events up to about 50,000 years old.

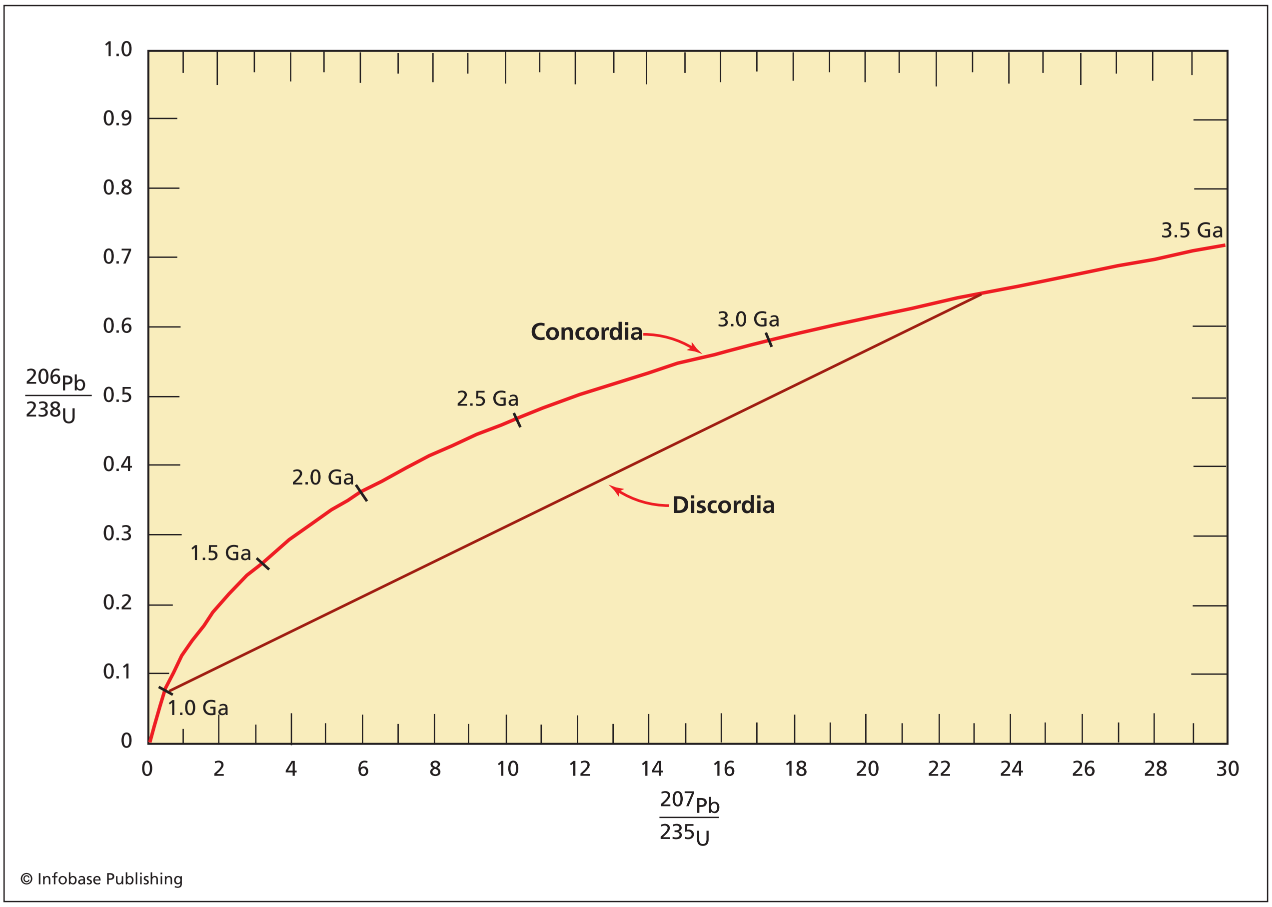
Dendrochronology is the study of annual growth rings in trees for dating the recent geological past. The ages of trees may be determined most simply by counting the number of annual growth rings that form in the trunk of the tree each year. Sometimes this practice is done in conjunction with carbon 14 or other dating techniques to verify the ages of specific rings. This field is closely related to dendroclimatology, the study of the sizes and relative patterns of tree growth rings to yield information about past climates. Tree rings are most clearly developed in species from temperate forests but not well formed in tropical regions, where seasonal fluctuations are not as great. Most annual tree rings consist of two parts, and early wood consisting of widely spaced thin-walled cells, followed by late wood, consisting of thinly spaced, thick-walled cells. The changes in relative width and density of the rings for an individual species correlates to changes in climate such as soil moisture, sunlight, precipitation, and temperature and also reflects unusual events such as fires or severe drought stress.

The longest dendrochronology record goes back 9,000 years, using species such as the Bristle Cone Pine, found in the southwestern United States, and Oak and Spruce species from Europe. To extend the record from a particular tree, one can correlate rings between individuals that lived at different times in the same microenvironment close to the same location.

Uranium, thorium, and lead isotopes form a variety of geochronometers using different parent/daughter pairs. Uranium 238 decays to lead 206 with a half-life of 4.5 billion years. Uranium 235 decays to lead 207 with a half-life of 0.7 billion years, and thorium 232 decays to lead 208 with a half-life of 14.1 billion years. Uranium, thorium, and lead are generally found together in mixtures, and each one decays into several daughter products (including radium) before turning into lead. The thorium 230/uranium 234 disequilibrium method is one of the most commonly used uranium-series techniques and can be used to date features as old as Precambrian. The fact that uranium is much more soluble than thorium forms the basis for this method, so materials such as corals, mollusks, calcic soils, bones, carbonates, cave deposits, and fault zones are enriched in uranium with respect to thorium.

Uranium-lead dating also uses the known original abundance of isotopes of uranium and the known decay rates of parents to daughter isotopes. This technique is useful for dating rocks up to billions of years old. All naturally occurring uranium contains uranium 238 and uranium 235 in the ratio of 137.7:1. Uranium 238 decays to lead 206 with a half-life of 4,510 Ma through a process of eight alpha-decay steps and six beta-decay steps. Uranium 235 decays to Lead 207 (with a half-life of 713 Ma) by a similar series of stages that involves seven alpha-decay steps and four beta-decay steps. Uranium-lead dating techniques were initially applied to uranium minerals such as uraninite and pitchblende, but these are rare, so geochronologists developed precise methods of measuring isotopic ratios in other minerals with only trace amounts of uranium and lead (zircon, sphene). The amount of radiogenic lead in all these methods must be distinguished from naturally occurring lead; this is calculated using their abundance with lead 204, which is stable. After measuring the ratios of each isotope relative to lead 204, the ratios of uranium 235/lead 207 and uranium 238/lead 206 should give the same age for the sample, and a plot with each system plotted on one axis shows each age. If the two ages agree, the ages will plot on a curve known as concordia, which tracks the evolution of these ratios in Earth versus time. Ages that plot on concordia are said to be concordant. In many cases, however, the ages determined by the two ratios are different, and they plot off the concordia curve. This occurs when the system has been heated or otherwise disturbed during its history, causing a loss of some of the lead daughter isotopes. Because lead 207 and lead 206 are chemically identical, they are usually lost in the same proportions.

The thorium-lead dating technique is similar to the uranium-lead technique; it uses the decay from thorium 232 to lead 208 (releasing six helium 4), with a half-life of 13,900 years. Minerals used for this method include sphene, zircon, monazite, apatite, and other rare U-Th minerals. The ratio of lead 208/thorium 232 is comparable with lead 207/uranium 235. This not totally reliable method is usually employed in conjunction with other methods. In most cases the results are discordant, showing a loss



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Concordia diagram showing the concordia curve that traces the evolution of the $^{206}Pb/^{238}U$ vs. $^{207}Pb/^{235}U$ ratio with time, from the present to 3.5 billion years (Ga) ago. The discordia curve shows the path that the ratio would follow if the rock example used crystallized at 3.2 billion years ago and lost lead (for example, through metamorphism) at 1.0 billion years ago.

of lead from the system. The Th-Pb method can also be interpreted by isochron diagrams.

Potassium-argon dating is based on the decay of radioactive potassium into calcium and argon gas at a specific rate and is accomplished by measuring the relative abundances of potassium 40 and argon 40 in a sample. The technique is potentially useful for dating samples as old as 4 billion years. Potassium is one of the most abundant elements in Earth's crust (2.4 percent by mass). One out of every 100 potassium atoms is radioactive potassium 40, with 19 protons and 21 neutrons. If a beta particle hits one of the protons, the latter can convert into a neutron. With 18 protons and 22 neutrons, the atom becomes argon 40, an inert gas. For every 100 potassium 40 atoms that decay, 11 become argon 40.

By comparing the proportion of potassium 40 to argon 40 in a sample and knowing the decay rate of potassium 40, one can estimate the age of the sample. The technique works well in some cases but is unreliable in samples that have been heated or recrystallized after formation. Since it is a gas, argon 40 can easily migrate in and out of potassium-bearing rocks, changing the ratio between parent and daughter.

Fission-track dating determines the thermal age of a sample, the time lapsed since the last significant heating event (typically above 215°F, or 102°C). Fission tracks are paths of radiation damage made by nuclear particles released by the spontaneous fission, or radioactive decay, of uranium 238. Fission tracks are created at a constant rate in uranium-bearing minerals, so by determining the density of tracks present, one can determine the amount of time that has passed since the tracks began to form in the mineral. Fission-track dating is used for determining the thermal ages of samples between about 100,000 and 1,000,000 years old; it is also used for estimating the uplift and erosional history of areas by recording when specific points cooled past 215.6°F (102°C).

Thermoluminescence is a chronometric dating method based on the fact that some minerals give off a flash of light when heated. The intensity of the light is proportional to the amount of radiation to which the sample has been exposed and the length of time since the sample was heated. Luminesence results from heating a substance, and thus liberating electrons trapped in its crystal defects. The phenomenon is used as a dating technique, especially for pottery. The number of trapped electrons is assumed to be related to the quantity of ionizing radiation to which the specimen has been exposed since firing, since the crystal defects are caused by ionizing radiation, and therefore the sample's age. Thus, measuring the amount of light emitted upon heating allows one to estimate of the age of the sample.

A number of other isotopic systems can be used for geochronology, but they are less common or less reliable than the methods described above. Geochronologists also incorporate relative and correlation dating techniques, such as stratigraphic correlation of dated units, to explore the wider implications of ages of dated units. A paleomagnetic timescale has been constructed for the past 180 million years, and in many situations one can determine the age of a particular part of a stratigraphic column or location on the seafloor by examining the geomagnetic properties of that position on the column and correlating it with a known geomagnetic period. Finally, geochronologists use structural cross-cutting relationships to determine which parts of a succession are older or younger than a dated sample. Eventually the geochronologist is able to put together a temporal history of a rock terrane by dating several samples and combining these ages with cross-cutting observations and correlation with other units.

See also PALEOMAGNETISM; RADIOACTIVE DECAY; STRATIGRAPHY, STRATIFICATION, CYCLOTHEM.

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geodesy Geodesy is the study of the size and shape of the Earth, its gravitational field, and the determination of the precise locations of points on the surface. This branch of geology also includes the study of the temporal variations in the shape of the planet and the location of points on the surface as a result of tides, rotation, and plate tectonic movements. Geodetic measurements rely heavily on positional measurements from satellite-based global positioning systems, gravity measurements, and radar altimetry measurements over the oceans. The science of measuring the size of the Earth probably started with Erastosthenes in ancient Greece, who measured the distance from Alexandria to Aswan in Egypt and calculated the curvature of the Earth from his measurements.

One branch of geodesy deals with the measurement of the Earth's gravity field and the geoid, the surface of equal gravitational potential. A person's weight, or the pull of the Earth's gravity on a person, would be the same everywhere on this surface. Since the Earth has internal irregularities in density, this surface is itself irregular. The geoid has a roughly elliptical shape that is slightly flattened at the poles as a result of the planet's rotation, and the shape of this surface is approximated by a reference ellipsoid. Variations in the height of the geoid from the reference ellipsoid are expressed as the geoid height, in many cases reaching 30–50 feet (tens of meters). These variations reflect variations in the mass distribution within the Earth, and smaller, temporary variations may result from tides or winds changing the mass distribution of the oceans.

Geodetic measurements must use some reference frame, typically an astronomical or celestial, or an inertial reference frame. Many geodetic measurements are between different points on the surface, and these terrestrial measurements are useful for determinations of surface deformation such as motion along faults. Regional geodetic measurements rely on the art of triangulation, first developed by the Dutch scientist Gemma Frisius in the 16th century. Triangulation uses precise measurements of the angles and distances between different points in a network or grid to determine the changes in the shape of the grid with time, and hence the deformation of the surface.

Space geodesy uses satellite positioning techniques where GPS satellites emit microwave signals encoded with information about the position of the satellite and the precise time at which the signal left the satellite. The microwave signals are received and decoded by the GPS receivers on the ground, and the distance to the satellite is calculated by knowing the time it took for the signal to travel from the satellite to the receiver using the speed that microwave signals travel through the atmosphere. The resulting calculation gives a result that the receiver may be anywhere on a sphere around the satellite, but the range of possible locations can be narrowed since the receiver is typically on the surface of the Earth. The use of multiple GPS satellite signals allows for the determination of the precise position on the surface of the Earth by finding the unique location where the calculated spheres around the multiple GPS satellites intersect on the surface. The accuracy of GPS positions can be a few feet (1 meter or less) and can be improved by the technique of differential GPS, in which a satellite receiver at a known position is coupled with and emits signals to a roving receiver. Furthermore, multireceiver interferometric and kinematic GPS techniques can improve positional measurements to the submillimeter level. The improved precision for these methods has greatly improved observations of surface deformation needed to predict earthquakes and volcanic eruptions and has aided precise navigation, surveying, and guidance systems.

See also GEOGRAPHIC INFORMATION SYSTEMS; GEOID; GEOPHYSICS; REMOTE SENSING.

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geodynamics Geodynamics is the branch of geophysical science that deals with forces and physical processes in the interior of the Earth necessary to understand plate tectonics and many other geological phenomena. This field of geology typically involves the macroscopic analysis of forces associated with a process and may include mathematical or numerical modeling. Geodynamics is a quantitative science closely related to geophysics, tectonics, and structural geology with problems including assessment of the forces associated with mantle convection, plate tectonics, heat flow, mountain building, erosion, volcanism, fluid flow, and other phenomena. The aim of many studies in geodynamics is to assess the relationships between different processes, such as to determine the influence of mantle convection on plate movements or to assess plate motions in one area with deformation in another. It is contrasted with many other types of geological studies that tend to be either static, analyzing only present and past states, or kinematic, which analyze the history of motions without a quantitative assessment of the forces involved.

Geodynamics is largely concerned with consideration of the fundamental physical processes that drive plate tectonics and how to interpret signatures of the products of plate interactions. To achieve these goals geodynamics typically takes a continuum mechanical approach to understanding stress and strain in solid materials, and takes a quantitative approach to modeling flexure of materials, and then applies this to studies of the Earth's lithosphere. Studies of heat transfer form a major component of the field of geodynamics. Heat is produced within the Earth and may be transferred by conduction, convection, or advection. Studying heat flow and transfer equations is necessary to understand the role of these different mechanisms in the Earth. Heat transfer and flow and the temperature of Earth materials all play major roles in how the mantle behaves and in how internal processes drive plate tectonics on the surface.

Measurements of gravity and magnetic fields can yield information about the structure and composition of materials at depth. To obtain realistic interpretations of gravity and magnetic anomalies and their causes, it is first necessary to understand such concepts as gravitational acceleration, the geoid, gravity fields of masses at depth, and techniques to model these physical processes.

Fluid mechanics falls in the realm of geodynamics, including flow in the asthenosphere, flow of magma through subvolcanic feeder systems and in lava tubes, flow of material into (and out of) subduction zones, as well for understanding mantle flow associated with glacial rebound. Thermal convection is modeled in fluid dynamics and has obvious applications to mantle convection, the driving forces of plate tectonics, and also to systems such as modeling fluid flow around hot springs, submarine black smoker chimneys, and geological mineral deposits formed by circulating hot fluids.

Geodynamics is concerned with the rheology or mechanical behavior of materials and how strain is accommodated at the crystal lattice and atomic scales, then applies the physics at these scales to the deformation of the mantle, asthenosphere, and lithosphere. Brittle and ductile/brittle deformation mechanisms can be modeled in geodynamics, including the mechanics of thrust-faulted terranes, the geometry of faulting, extensional fault systems, and strike-slip fault systems.

Flow of fluids in porous media is studied in geodynamics, with applications to flow of water in aquifers, petroleum and hydrocarbons in reservoirs, and general flow laws for fluids moving through any porous or fractured medium.

See also CONVECTION AND THE EARTH'S MANTLE; CRYSTAL, CRYSTAL DISLOCATIONS; ENERGY IN THE EARTH SYSTEM; GEOPHYSICS; PLATE TECTONICS.

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geographic information systems (GIS)

Geographic information systems (GIS) are computer application programs that organize and link information to enable users to manipulate that information constructively. They typically integrate a database management system with a graphics display that shows links between different types of data. For instance, a GIS may show relationships among geological units, ore deposits, and transportation networks. GIS allows users to layer information over other information already in the database. A GIS database allows the storage of information in a particular geographical area no matter what that information may be.

GIS is a powerful tool for environmental data analysis and planning, allowing for better viewing and modeling of changing environmental conditions and the relationships that influence a given critical environmental setting. Many fields have come to rely on GIS for data collection and analysis, including environmental and health science studies concerned with risk assessment and mitigation, environmental modeling, resources exploration, sustainable development, natural resource management, transportation, air pollution and control, and forest fire management. GIS is used widely in science, industry, business, and government to sort out pertinent information for the particular user from the GIS database.

For a GIS to be accurate the data must be entered with precise knowledge of the location of features on the ground, referenced to a map grid or reference frame. Benchmarks are well-defined, uniformly fixed points on the land's surface used for reference points from which other measurements can be made. They are generally marked by circular bronze disks with a diameter of 3.75 inches (10 cm) and are embedded firmly in bedrock or another permanent structure. In the United States benchmarks are installed and maintained by the U.S. Coast and Geodetic Survey and the U.S. Geological Survey. The elevations of many benchmarks were in the past established by the surveying technique of differential leveling. Now it is more common to determine elevations with satellite-based differential global positioning systems. Benchmarks, often identified on topographic maps by the abbreviation B.M., are used for determining elevation and for surveying and construction.

Geographic information systems are typically used in conjunction with global positioning systems to collect spatially accurate location data in the field. Global positioning systems, commonly referred to by their acronym GPS, were developed by the U.S. Department of Defense to provide the U.S. military with a superior tool for navigation, viable at any arbitrary point around the world. The Defense Department pays billions of dollars for the development and maintenance of the GPS program, which has matured a great deal since its conception in the 1960s.

The configuration of the global positioning system includes three main components: the GPS satellites, the control segment, and the GPS receivers. Working together these components provide users of GPS devices with their precise location on the Earth's surface, along with other basic information of substantial use such as time, altitude, and direction. Key to understanding how GPS functions is the understanding of these components and how they interrelate with one another.

GPS satellites, named Navstar Satellites, form the core of the global positioning system. Navstar satellites are equipped with an atomic clock and radio equipment to broadcast a unique signal, called a "pseudorandom code," as well as ephemeris data about the exact position of the satellite relative to Earth and astromical reference frames. This signal distinguishes one satellite from the other and provides GPS receivers accurate information about the exact location of the satellite. These satellites follow a particular orbit around the Earth, and their sum is called a constellation. The GPS Navstar satellite constellation is configured so that at any point on Earth's surface, the user of a GPS receiver should be able to detect signals from at least six Navstar satellites. It is essential to the proper functioning of GPS that the precise configuration of the constellation be maintained.

Geosynchronous satellite orbit maintenance is performed by the control segment (or satellite control centers), with stations in Hawaii, Ascension Island, Diego Garcia, Kwajalein, and Colorado Springs. Should any satellite fall slightly in altitude or deviate from its correct path, the control segment will take corrective actions to restore precise constellation integrity.

Finally, the component most visible to all who use GPS devices is the GPS receiver. GPS receivers are single-direction, asynchronous communication devices; the GPS receiver does not broadcast any information to the Navstar satellites but only receives signals from them. Recent years have seen the miniaturization and mass proliferation of GPS receivers. GPS devices are now so small that they can be found in many other hybrid devices such as cellular phones, some radios, and personal desk accessories. They are also standard on many vehicles for land, sea, and air travel. Accuracy of consumer GPS receivers is typically no better than nine feet (2.7 m), but advanced GPS receivers can measure location to less than a centimeter.

GPSs resolve a location on the surface of Earth through trilaterating, a process that determines the distances to the Navstar satellites and the GPS receiver. To do this two things must be true. The locations of the Navstar satellites must be known and there must be a mechanism for precision time measurements. For very precise measurements there must be a system to reconcile error caused by various phenomena.

GPS receivers are programmed to calculate the location of all the Navstar satellites at any given time. A combination of the GPS receiver's internal clock and trilateration signal reconciliation, performed by the GPS receiver, allow a precise timing mechanism to be established.

When a GPS receiver attempts to locate itself on the surface of the planet, it receives signals from the Navstar satellites. As mentioned previously, these signals are intricate and unique. By measuring the time offset between the GPS receiver's internal pseudorandom code generator and the pseudorandom code signal received from the Navstar satellites, the GPS receiver can use the simple-distance equation to calculate the distance to the Navstar satellite.

To locate a point on Earth's surface accurately, at least three distances must be measured. One measurement is enough only to place the GPS receiver within a three-dimensional arc. Two measurements can place the receiver within a circle. Three measurements place it on one of two points. One possible point location is usually floating in space or traveling at some absurd velocity, so the GPS receiver eliminates this point as a possibility, thus resolving the GPS receiver's location on the surface of the planet. A fourth measurement allows the correct point to be located, as well as provides necessary geometry data to synchronize the GPS receiver's internal clock to the Navstar satellite's clock.

Depending on the quality of the GPS device, error correction may also be performed when calculating location. Errors arise from many sources. Atmospheric conditions in the ionosphere and troposphere cause impurities in the simple-distance equation by altering the speed of light. Weather modeling can help calculate the difference between the ideal speed of light and the likely speed of light as it travels through the atmosphere. Calculations based on the corrected speed of light then yield more accurate results.

As weather conditions rarely fit models, however, other techniques such as dual frequency measurements, in which two different signals are compared to calculate actual speed of the pseudocode signal, are used to reduce atmospheric error.

Ground interference, such as multipath error, which arises from signals bouncing off objects on Earth's surface, can be detected and rejected in favor of direct signals via complicated signal-selection algorithms.

Still another source of error can be generated by the Navstar satellites' being slightly out of position. Even a few meters from the calculated position can throw off a high-precision measurement.

Geometric error can be reduced by using satellites that are far apart rather than close together, as this creates larger distances between satellites, easing certain geometric constraints.

Sometimes precision down to the centimeter is needed. Only advanced GPS receivers can produce precise and accurate measurements at this level. Advanced GPS receivers utilize one of several techniques to pinpoint more precisely locations on Earth's surface, mostly by reducing error or using comparative signal techniques.

One such technique is differential GPS, which involves two GPS receivers. One receiver monitors variations in satellite signals and relates this information to the second receiver. With this information the second receiver is then able to determine more accurately its location through better error correction.

Another method involves using the signal carrier-phase as a timing mechanism for the GPS receiver. As the signal carrier is a higher frequency than the pseudorandom code it carries, carrier signals can be used to synchronize timers more accurately.

Finally, a geostationary satellite can be used as a relay station for transmission of differential corrections and GPS satellite data. Called augmented GPS, this is the basic idea behind the new WAAS system installed in North America. The system encompasses 25 ground-monitoring stations and two geostationary WAAS satellites that allow for better error correction. This sort of GPS is necessary for aviation, particularly in landing sequences.

See also REMOTE SENSING.

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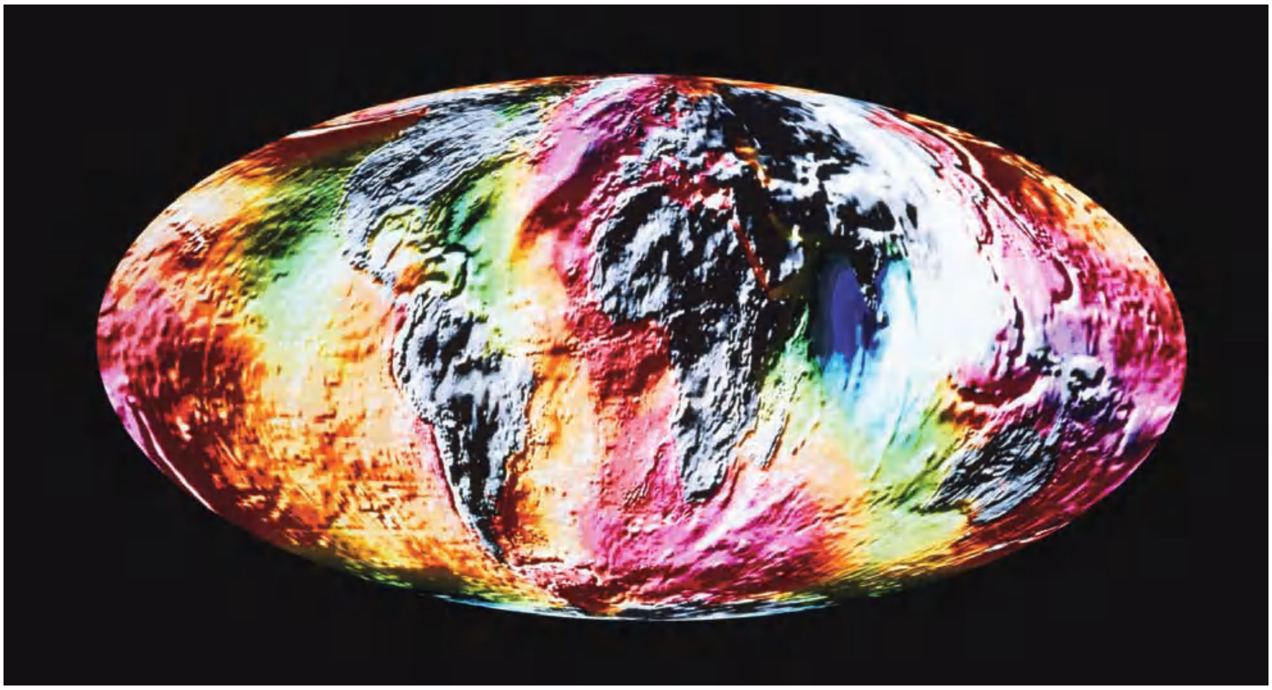
geoid The geoid is an imaginary surface near the surface of the Earth, along which the force of gravity is the same and equivalent to that at sea level. This so-called equipotential surface can be thought of as equivalent with sea level and extending through the continents on the Earth, and is often referred to as the figure of the Earth. Theoretically it exists everywhere perpendicular to the direction of gravity (the plumb line) and is used as a reference surface for geodetic measurements. If the Earth were spherically symmetric and not spinning, the gravitational equipotential surfaces would consist of a series of concentric shells with increasing potential energy extending away from the Earth, much like raising a ball to a higher level increases its potential energy. Since the Earth is not perfectly spherical (it is a flattened oblate spheroid) and it is spinning, however, the gravitational potential is modified so that it is an oblate spheroid with its major axis 0.3 percent longer than the minor axis. A best-fit surface to this spheroid is used by geodeticists, cartographers and surveyors, but in many places the actual geoid departs from this simple model shape. Nonuniform distributions of topography and mass with depth cause variations in the gravitational attraction, phenomena known as geoid anomalies. Areas of extra mass, such as mountains or dense rocks at depth, cause positive geoid anomalies known as geoid highs, whereas mass deficits cause geoid lows. The geoid is measured by a



Ocean surface topography. Colors depict deviation from mean ocean surface caused by local differences in the Earth's gravitational field. Purple is up to 280 feet (85 m) above mean, through red, orange, yellow, green, to blue (up to 345 feet [105 m] below mean). *(GFZ/Photo Researchers, Inc.)*

variety of techniques, including direct measurements of the gravity field on the surface, tracking of satellite positions (and deflections due to gravity), and satellite-based laser altimetry that can measure the height of the sea surface a fraction of an inch (the subcentimeter level). Variations in the height of the geoid are typically tens to 50 feet, but range up to 450 feet (tens to even more than 100 meters).

The geoid is considered the baseline figure of the Earth, which can be considered a sea-level surface including local gravitational effects without taking into account topographic features. The geoid surface is continuous over the entire surface of the Earth. Calculating the surface of equal potential energy would yield a map close to that of the sea-surface topography as measured by satellite without the effect of motion of the water, but the true sea-surface topography differs from the geoid from the effects of ocean currents. Oceanographers use this relationship to map ocean circulation patterns, including complex eddies, by removing the height of the sea surface caused by gravity and examining the remaining anomalies caused by motion of the water.

See also GEOPHYSICS; SUPERCONTINENT CYCLES.

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geological hazards Geological hazards take many shapes and forms, from earthquakes and volcanic eruptions to the slow, downhill creep of material on a hillside and the expansion of clay minerals in wet seasons. Natural geologic processes constantly operate on the planet. They are considered hazardous when they go to extremes and interfere with the normal activities of society. For instance, the surface of the Earth constantly moves through plate tectonics yet is not noticeable until sections of the surface move suddenly, causing an earthquake.

The Earth is a naturally dynamic, hazardous world, with volcanic eruptions spewing lava and ash, earthquakes pushing up mountains and shaking Earth's surface, and tsunamis that sweep across ocean basins at hundred of miles per hour (500 km/hr), rising in huge waves on distant shores. Mountains may suddenly collapse, burying entire villages under massive landslides. Other mountain slopes are gradually creeping downhill, slowly tilting and moving everything built on them farther downslope. Storms sweep coastlines and remove millions of tons of sand from one place and deposit it in another in a single day. Large parts of the globe are turning into desert. Glaciers that once advanced are rapidly retreating, and sea level is beginning to rise faster than previously imagined. All of these natural phenomena are expected consequences of the way the planet works, and as scientists better understand these geological processes, they are better able to predict when and where natural geologic hazards could become disasters and take preventative measures.

The slow but steady movement of tectonic plates on the surface of the Earth is the cause of many geologic hazards, either directly or indirectly. Plate tectonics controls the distribution of earthquakes and the location of volcanoes, and causes mountains to be uplifted. Other hazards are related to Earth's surface processes, including floods of rivers, coastal erosion, and changing climate zones. Many of Earth's surface processes are parts of natural cycles but are considered hazardous to humans because people did not adequately understand the cycles before building on exposed coastlines and in areas prone to shifting climate zones. A third group of geologic hazards is related to materials such as clay minerals that dramatically expand when wetted, and sinkholes that develop in limestones. Still other hazards are extraterrestrial in origin, such as the occasional impact of meteorites and asteroids with Earth. The exponentially growing human population on Earth worsens the effect of most of these hazards. Species on the planet are now experiencing a mass extinction event, the severity of which has not been seen since the extinction event 66 million years ago that killed the dinosaurs and many other species at that time.

Many geologic hazards are the direct consequence of plate tectonics, associated with the motion of individual blocks of the rigid outer shell of the Earth. With so much energy loss accommodated by plate tectonics, it is clear why plate tectonics is one of the major energy sources for natural disasters and hazards. Most of the earthquakes on the planet are directly associated with plate boundaries, and these sometimes devastating earthquakes account for much of the motion between the plates. Single earthquakes have killed tens and even hundreds of thousands of people, such as the 1976 Tangshan earthquake in China that killed a quarter million people, and the 2008 Sichuan earthquake that killed about 100,000 people in southern China. Earthquakes also cause enormous financial and insurance losses; for instance, the 1994 Northridge, California, earthquake caused more than $14 billion in losses. Most of the world's volcanoes are also associated with plate boundaries. Thousands of volcanic vents are located along the midocean ridge system, and

Mudflow on Whangaehu River after lahar from crater lake of Mount Ruapehu in the central North Island of New Zealand, March 18, 2007: The bridge over river is Tangiwai road bridge. *(Anthony Phelps/Reuters/Landov)*

most of the volume of magma produced on the Earth is erupted through these volcanoes. Volcanism associated with the midocean ridge system is rarely explosive, hazardous, or even noticed by humans. In contrast, volcanoes situated above subduction zones at convergent boundaries are capable of producing tremendous explosive eruptions, with great devastation of local regions. Volcanic eruptions and associated phenomena have killed tens of thousands of people in the 20th century, including the massive mudslides at Nevada del Ruiz, Colombia, that killed 23,000 in 1985. Some of the larger volcanic eruptions cover huge parts of the globe with volcanic ash and are capable of changing the global climate. Plate tectonics is also responsible for uplifting the world's mountain belts, which are associated with their own sets of hazards, particularly landslides and other mass wasting phenomena.

Pyroclastic flow on Mayon volcano in Legazpi City, Philippines, March 7, 2000 *(AP Images)*

Some geologic hazards are associated with steep slopes and the effects of gravity moving material down these slopes to inhabited areas. Landslides and the slow downhill movement of earth material occasionally kill thousands in large disasters, such as when parts of a mountain collapsed in 1970 in the Peruvian Andes and buried a village several tens of miles away, killing 60,000 people. Downhill movements are typically more localized and destroy individual homes, neighborhoods, roads, or bridges. Some downslope processes are slow and involve the inch-by-inch (cm by cm) creeping of soil and other earth material downhill, taking everything with it during its slide. Creep is one of the costliest of natural

LIQUEFACTION AND LEVEES: POTENTIAL DOUBLE DISASTER IN THE AMERICAN MIDWEST

Liquefaction is a process during which sudden shaking of certain types of water-saturated sands and muds turns these once-solid sediments into a slurry having a liquidlike consistency. Liquefaction occurs when shaking causes individual grains in the soil to move apart, then water moves between the grains, making the whole water/sediment mixture behave like a fluid. Earthquakes often cause liquefaction of sands and muds, and any structures built on soils or sediments that liquefy may suddenly sink into them as if they were resting on a thick fluid. Liquefaction causes sand to bubble to the surface during earthquakes, forming mounds up to several tens of feet (~ 10 m) high, known as sand volcanoes, and ridges of sand to squeeze into cracks in the Earth. Liquefaction is responsible for the sinking of sidewalks, telephone poles, building foundations, and other structures during earthquakes. Famous examples of liquefaction occurred in the 1964 Alaskan earthquake, when entire neighborhoods slid toward the sea on liquefied sand layers, and in the 1964 and 1995 Japan earthquakes, when entire rows of apartment buildings and shipping piers rolled onto their sides but were not severely damaged internally.

Recent earthquakes and floods in the Midwest region of the United States passed with locally huge amounts of damage, but were not catastrophic events for the entire region. But one must consider what could have happened if the earthquakes were slightly larger (which is possible) and occurred while the rivers were at high stages (which happens for several months each year). One real threat is that many apparently stable levees may experience mass failure by liquefaction during an earthquake, potentially causing catastrophic flooding of regions behind these levees.

The U.S. Geological Survey reports that there is a significantly high threat of many of the soils on the floodplains of the Mississippi, Missouri, Ohio, and Illinois Rivers—in a report to the U.S. House of Representatives in 2006, Eugene Schweig (of the U.S. Geological Survey) stated, “If the earthquakes were to occur when the Ohio and Mississippi Rivers were high, loss of levees is likely along with flooding of low-lying communities.” When the soils in the levees are saturated with water, such as during flood or high-water events, the potential for liquefaction is much higher. Geological analysis of the banks of many rivers in the region has revealed that a magnitude 6 or 7 earthquake struck about 40 miles (65 km) east of St. Louis some 6,500 years ago, and another event struck about 4,000 years ago. Both events caused massive liquefaction of the thick river sediments on the floodplains. Large earthquakes have continued to hit the region in historic times, as shown by the 1811–12 sequence of magnitude 7–8 events, which also caused liquefaction of huge areas in southern Missouri and surrounding states. The April 18, 2008, earthquake in Illinois and aftershocks remind and warn us that the potential consequences of earthquakes on levees during high water must be considered.

The two earthquake swarms in the Midwest in 2008, although minor, occurred when the local rivers were high. What would have happened if the earthquakes were slightly larger, say a magnitude 6 or 7? Would the levees have experienced mass failure and collapse by liquefaction? Levees fail for several reasons. They may be overtopped by high water, scoured at their bases and sides, or have water seep through the pores between the sand and mud, weakening the structure until the pressure from the high water causes it to collapse. The most catastrophic type of failure can occur when the soils of the levee liquefy from the pressure of the high water, by shaking from earthquakes, or both. In these types of failures, hundreds of linear yards of levee may suddenly collapse, sending torrents of water into the “protected” areas behind the levees. Studies by the U.S. Army Corps of Engineers suggest that many of the levees in the region are not strong enough to withstand shaking during an earthquake and may fail by liquefaction. The problem is especially critical in communities such as those surrounding East St. Louis, Illinois, where the entire levee system is in the process of being decertified, as the levees do not meet modern standards for safety in earthquakes and from other stresses, such as floods. If these levees fail during high water, the force of the Mississippi will surge into East St. Louis with the force of Niagara Falls, pushing into and covering the floodplain with many feet (several m) of water. Approximately 130,000 people live on the floodplain in the Metro East area near East St. Louis and rely on the levees for protection. If an earthquake causes massive liquefaction and failure of the levees, there will be little time to react, and many people will be stranded on rooftops, creating scenes reminiscent of New Orleans and Hurricane Katrina.

What can be done? The U.S. Army Corps of Engineers estimated that it will take $180 million to upgrade the Metro East levees to modern standards, and much of that money would need to come from local communities. If that is too expensive, residents on the floodplain behind the levees need to be aware of the possibility of liquefaction and mass failure of the levee system. Flood-hazard and earthquake-hazard risk maps need to be compared to determine which areas have the greatest threat for liquefaction, and emergency management plans need to be established for the contingency of such a catastrophe. This could save many lives. Homeowners, businesses, local governments, and insurance issuers need to understand these risks and plan accordingly.

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Debris in Galle, Sri Lanka, after tsunami, December 27, 2004 *(AP Images)*

hazards, for which American taxpayers pay billions of dollars each year.

Many other geological hazards are driven by energy from the Sun and reflect the interaction of the hydrosphere, lithosphere, atmosphere, and biosphere. Heavy or prolonged rains can cause river systems to overflow, flooding low-lying areas and destroying towns, farmlands, and changing the course of major rivers. There are several types of floods, ranging from flash floods in mountainous areas to regional floods in large river valleys such as the great floods of the Mississippi and Missouri Rivers in 1993. Coastal regions may also experience floods, sometimes the result of typhoons, hurricanes, or coastal storms that bring high tides, storm surges, heavy rains, and deadly winds. Coastal storms can cause large amounts of coastal erosion, including cliff retreat, beach and dune migration, and opening of new tidal inlets and closing of old inlets. All these normal beach processes have become hazardous since so many people have migrated into beachfront homes. Hurricane Andrew caused more than $19 billion of damage to the southern United States in 1992.

Deserts and dry regions are associated with their own natural geologic hazards. Blowing winds and shifting sands hinder agricultural efforts, and deserts have a limited capacity to support large populations. Some of the greatest disasters in human history have been caused by droughts, some associated with the expansion of desert regions into areas that previously received significant rainfall and supported large populations dependent on agriculture. In this century the sub-Saharan Sahel region of Africa has been hit with drought disasters several times, affecting millions of people and animals. This appears to be part of a natural climate cycle of alternating wet and dry periods in the Sahara. Contraction and expansion of the desert fringes has severe consequences for those who try to live in such changing conditions.

Desertification is but one possible manifestation of global climate change. The Earth has fluctuated in climate extremes, from hot and dry to cold and dry or cold and wet, and has experienced several periods when much of the land's surface was covered by glaciers. Glaciers have their own set of local-scale hazards that affect those living or traveling on or near their ice crevasses, which can be deadly if fallen into. Glacial meltwater streams can change in discharge so quickly that encampments on their banks can be washed away without a trace, and icebergs present hazards to shipping lanes. More important, glaciers reflect subtle changes in global climate—when glaciers are retreating, climate may be warming and becoming drier. When glaciers advance, the global climate may be getting colder and wetter. Glaciers have advanced and retreated over northern North America several times in the past 100,000 years. The Earth is currently experiencing an interglacial episode and may see the start of the return of the continental glaciers over the next few hundred or thousand years.

Geologic materials themselves can be hazardous. Asbestos, a common mineral, is being removed from thousands of buildings in the United States because of the threat that certain types of airborne asbestos fibers present to human health. In some cases (for certain types of asbestos fibers), this threat is real and removal of the fibers is necessary. In other cases leaving the asbestos alone is safer than disturbing it and releasing airborne particles. Natural radioactive decay releases harmful gases, including radon, that creep into homes, schools, and offices, and causes numerous cases of cancer every year. Mitigating this hazard is often easy—simple monitoring and ventilation can prevent many health problems associated with radon exposure. Other materials can be hazardous even though they seem inert. For instance, some clay minerals expand by hundredsfolds when wetted. These expansive clays rest under many foundations, bridges, and highways, and cause billions of dollars of damage every year in the United States.

Sinkholes, including the one in Winter Park, Florida, have swallowed homes and businesses in Florida and in other locations in recent years. Sinkhole collapse and other subsidence hazards are more important than many realize. Large parts of southern California near Los Angeles have sunk tens of feet (about 10 meters) in response to pumping of groundwater and oil out of underground reservoirs. Other developments above former mining areas have begun sinking into collapsed mine tunnels. Coastline areas experiencing subsidence face the added risk of having the ocean rise into former living space. Coastal subsidence coupled with gradual sea-level rise is rapidly becoming one of the major global hazards that humans must deal with in the next century, since most of the world's population lives near the coast in the reach of the rising waters. Cities may become submerged and farmlands covered by shallow salty seas. New Orleans and much of the Gulf coast have been sinking at rates of up to one inch per year (2.5 cm per year) in response to natural and human-induced processes, placing some urban areas at high risk for storm surge and hurricane damage. These risks were shown dramatically by Hurricanes Katrina and Rita in 2005. An enormous amount of planning is needed, as soon as possible, to deal with this growing threat.

Occasionally in the Earth's history the planet has been hit with asteroids and meteorites from outer space, and these have completely devastated the biosphere and climate system. Many of the mass extinctions in the geologic record are now thought to have been triggered, at least in part, by large impacts from outer space. For instance, the extinction of the dinosaurs and a huge percent of other species on Earth 66 million years ago is thought to have been caused by a combination of massive volcanism from a flood basalt province preserved in India, coupled with an impact with a six-mile (10-km) wide meteorite that hit the Yucatán Peninsula of Mexico. When the impact occurred, a 1,000-mile (1,610-km) wide fireball erupted into the upper atmosphere, a tsunami hundreds or thousands of feet (hundreds of meters) high washed across the Caribbean, southern North America, and much of the Atlantic, and huge earthquakes accompanied the explosion. The dust blown into the atmosphere immediately initiated a dark global winter, and as the dust settled months or years later, the extra carbon dioxide in the atmosphere warmed the Earth for many years, forming a greenhouse condition. Many forms of life could not tolerate these rapid changes and perished. Similar impacts at several times in the Earth's history have had a profound influence on the extinction and development of life.

The human population is growing at an alarming rate and currently doubling every 50 years. At this rate, there will be only a three-foot by one-foot space (1 square meter) for every person on Earth in 800 years. The unprecedented population growth has put such a stress on other species that we are driving a new mass extinction on the planet. Because details of the relationships between different species are unknown, many fear that destroying so many other life-forms may contribute to our own demise. In response to the population explosion, people are moving into hazardous locations including shorelines, riverbanks, along steep-sloped mountains, and along the flanks of volcanoes. Populations that grow too large to be supported by the environment usually suffer some catastrophe, disease, famine, or other mechanism that limits growth, and society needs to find ways to limit human population growth to sustainable rates. Survival of the planet depends on our ability to maintain these limits.

Advances in science and engineering in recent decades have dramatically changed perceptions of natural hazards. In the past people viewed destructive natural phenomena (including earthquakes, volcanic eruptions, floods, landslides, and tsunamis) as unavoidable and unpredictable. Society's attention to basic scientific research has changed that view dramatically, and the resulting ability to make general predictions regarding the timing, location, and severity of such destructive natural events reduces their consequences significantly. Communities can use this information to plan evacuations, strengthen buildings, and make detailed plans of what needs to be done in natural disasters to such a degree that their costs have been greatly reduced. Increased government responsibility accompanies this greater understanding. Formerly society hardly looked to government for aid in natural disasters. For instance, nearly 10,000 people perished in a hurricane that hit Galveston, Texas, on September 8, 1900, yet since there were no warning systems in place, no one was at blame. In 2001 two feet (0.6 m) of rain with consequent severe flooding hit the same area, and nobody perished, but billions of dollars of insurance claims were filed. When Hurricane Ike hit Galveston in 2008, most people evacuated and the loss of life was minimal.

Public perception of natural hazards and disasters has changed with the development of warning and protection systems, and few disasters occur without blame being assigned to public officials, engineers, or planners. Extensive warning systems, building codes, and increased understanding have certainly prevented the loss of thousands of lives, yet they also have given society a false sense of security. When an earthquake or other disaster strikes, people expect their homes to be safe, yet they were built to withstand only a certain level of shaking. When a natural geological hazard exceeds the expected level, a natural disaster with great destruction may result, and people often blame the government for not anticipating the event or preventing the destruction. However, planning and construction efforts are designed to meet only certain force levels for earthquakes and other hazards; planning for the rare stronger events would be exorbitantly expensive.

Geologic hazards can be extremely costly in terms of price and human casualties. With growing population and wealth, the cost of natural disasters has grown as well. The amount of property damage measured in dollars has doubled or tripled every decade, with individual disasters sometimes costing tens of billions of dollars. A 2000 report to the Congressional Natural Hazards Caucus estimated the costs of some recent disasters: Hurricane Andrew in 1992 cost $23 billion, the 1993 Midwest floods cost $21 billion, and the 1994 Northridge earthquake cost $45 billion. Recovery from Hurricane Katrina cost a staggering $80–200 billion, with some estimates exceeding $1 trillion. In contrast, the entire first Persian Gulf War cost the United States and its allies $65 billion. That the costs of natural geologic hazards are now similar to the costs of warfare demonstrates the importance of understanding their causes and potential effects.

See also EARTHQUAKES; ENERGY IN THE EARTH SYSTEM; HURRICANES; ISLAND ARCS, HISTORICAL ERUPTIONS; MASS WASTING; PLATE TECTONICS; VOLCANO.

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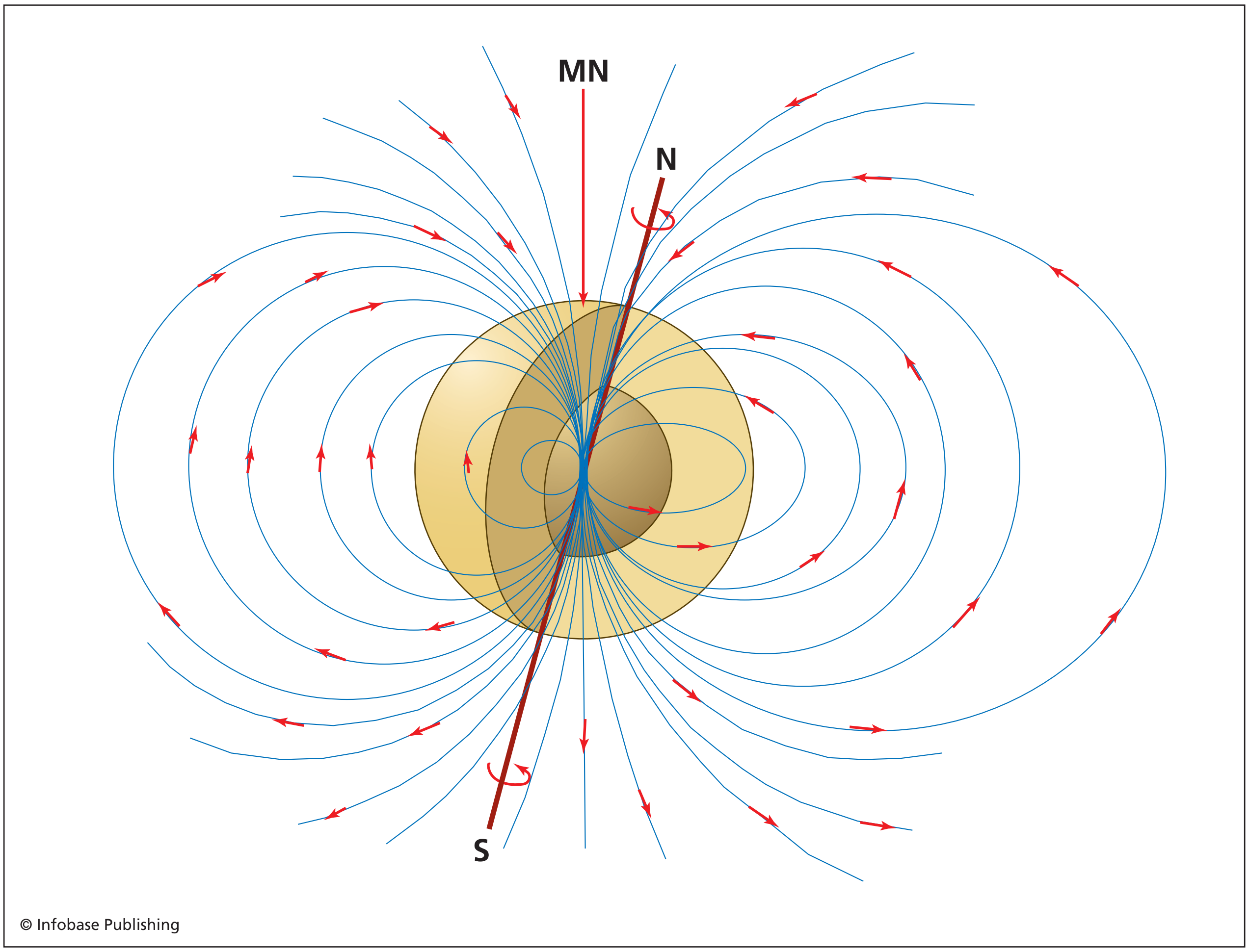
geomagnetism, geomagnetic reversal

The Earth has a magnetic field generated within the core of the planet. The field is generally approximated as a dipole, with north and south poles and magnetic field lines emerging from the Earth at the south pole and extending toward the north pole. The field is characterized at each place on the planet by an inclination and a declination. The inclination is a measure of how steeply inclined the field lines are with respect to the surface, with low inclinations near the surface, and steep inclinations near the poles. The declination measures the apparent angle between the rotational north pole and the magnetic north pole.

The magnetic field originates in the liquid outer core of the Earth and is thought to result from electrical currents generated by convective motions of the iron-nickel alloy that the outer core is made from.



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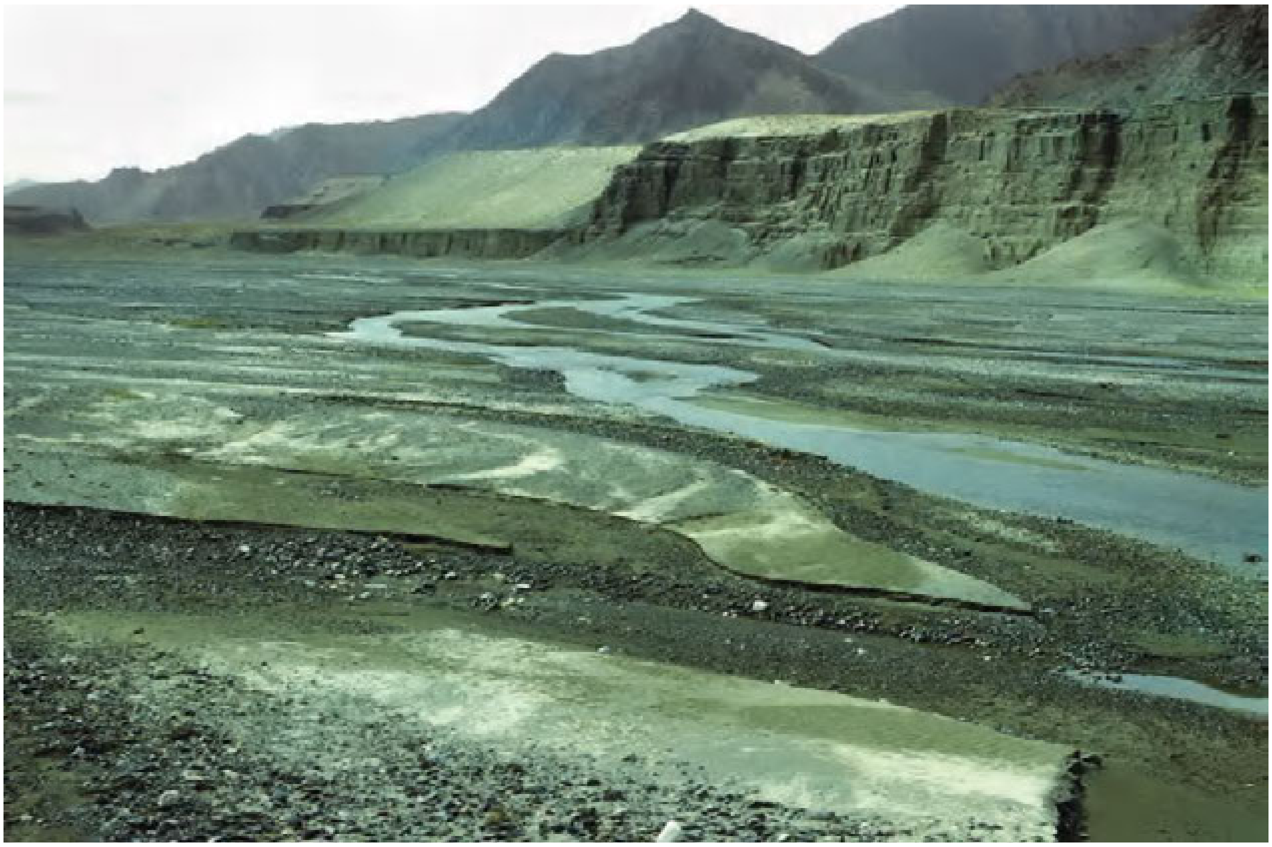
Magnetic field lines of Earth approximate the shape of the field produced by a bar magnet. Magnetic field lines point upward out of the south magnetic pole and form imaginary elliptical belts of equal intensity around Earth and plunge back into Earth at the magnetic north pole. Note how the magnetic poles are not coincident with the rotational poles. The orientation of the magnetic field at any point on Earth can be expressed as an inclination (plunge into Earth) and a declination (angular distance between the magnetic and rotational north poles).

The formation of the magnetic field by motion of the outer core is known as the geodynamo theory, pioneered by the German-American geophysicist and biologist Walter M. Elsasser (1904–91) of Johns Hopkins University in the 1940s. A dynamo generates electrical energy from mechanical energy. The basic principle for the generation of the magnetic field is that mechanical energy from the motion of the liquid outer core, which is an electrical conductor, is transformed into electromagnetic energy of the magnetic field. The convective motion of the outer core, maintained by thermal and gravitational forces, is necessary to maintain the field. If the convection stopped or the outer core solidified, the magnetic field would disappear. Secular variations in the magnetic field have been well documented by examination of the paleomagnetic record in the seafloor, lava flows, and sediments. Every few thousand years the magnetic field changes intensity and reverses, with the north and south poles abruptly flipping.

See also EARTH; GEOPHYSICS; PALEOMAGNETISM.

geomorphology Geomorphology is the description, classification, and study of the physical properties of and the origin of the landforms of the Earth's surface. Most studies in geomorphology include an analysis of the development of landforms and their relationships to underlying structures, and how the surface has interacted with other Earth systems such as the hydrosphere, cryosphere, and atmosphere. Geomorphologists have become increasingly concerned with the study of global climate change and the development of specific landforms associated with active deformation and tectonics. These relatively new fields of global change and active tectonic



Braided river channel and alluvial terraces on Golmud River in the Kunlun Mountains, Qinghai Province, China *(Fletcher & Baylis/Photo Researchers, Inc.)*

geomorphology represent a significant movement away from classical geomorphology, which is concerned mostly with the evolutionary development of landforms.

Geomorphological phenomena depend on many different processes that operate on the surface of the planet, so the geomorphologist needs to integrate hydrology, climate, sedimentology, geology, forestry, pedology, and many other sciences. This type of research has relevant applications to everyday life—for example, the decomposition of bedrock and the development of soils relate to global climate systems and also can help local engineers solve problems such as determining slope stability for construction sites. Other geomorphologists may study the development and evolution of drainage basins, along with the analysis of fluvial landforms such as floodplains, terraces, and deltas. Desert geomorphology is concerned with the development of desert landforms and climate, whereas glacial geomorphology analyzes the causes and effects of the movement of glaciers. Coastal processes including erosion, deposition, and longshore movement of sand are treated by coastal geomorphologists, whereas the development of various other types of landforms, such as karst, alpine, seafloor, and other terrains are treated by other specialists.

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geophysics Geophysics is the study of the Earth by quantitative physical methods, with different divisions including solid-Earth geophysics, atmospheric and hydrospheric geophysics, and solar-terrestrial physics. The many subdisciplines in the field include seismology, tectonics, geomagnetics, gravity, atmospheric science, ocean physics, and many others. Geophysics also includes the description and study of the origin and evolution of the major Earth systems, including the core, mantle, and crust of the continents and oceans. Geophysical methods include

- the use of tools of reflection and refraction seismology to use and measure the passage of sound waves through the Earth to mea-

sure the physical properties of the area in the Earth the waves pass through
- the use of electromagnetic sensors to quantify the electrical and magnetic properties of rocks
- potential field methods, which determine variations in gravity and magnetism across a region

SEISMOLOGY

Seismology is the study of the propagation of seismic, or sound, waves through the Earth, including analysis of earthquake sources, mechanisms, and the determination of the structure of the Earth through variations in the properties of seismic waves. The analysis is quantitative and typically requires high-powered computers.

The structure of the deep parts of the Earth can be mapped by seismology. Seismographs are stationed all over the world. Studying the propagation of seismic waves from natural and artificial sources, such as earthquakes, nuclear explosions, and other seismic events, allows for the calculation of changes in the properties of the Earth in different places. If the Earth had a uniform composition, seismic wave velocity would increase smoothly with depth because increased density is equated with higher seismic velocities. By plotting the observed arrival time of seismic waves, however, seismologists have found that the velocity does not increase steadily with depth, but that several dramatic changes occur at discrete boundaries and in transition zones deep within the Earth.

Seismologists calculate the positions and changes across these zones by noting several different properties of seismic waves. Some are reflected off interfaces, just as light is reflected off surfaces, and other waves are refracted, changing the velocity and path of the rays. These reflection and refraction events happen at specific sites in the Earth, and the positions of the boundaries are calculated by using wave velocities. The core-mantle boundary at 1,802 miles (2,900 km) depth in the Earth strongly influences both P- and S-waves. It refracts P-waves, causing a P-wave shadow and, because liquids cannot transmit S-waves, none gets through, causing a huge S-wave shadow. These contrasting properties of P- and S-waves can be used to map accurately the position of the core-mantle boundary.

Variation in the propagation velocity and direction of seismic waves illustrates several other main properties of the deep Earth. Velocity gradually increases with depth, to about 62 miles (100 km), where the velocity drops slightly between 62–124 miles (100–200 km) depth, in the low velocity zone. The reason for this drop in velocity is thought to be small amounts of partial melt in the rock, corresponding to the asthenosphere, the weak sphere on which the plates move, lubricated by partial melts.

Another seismic discontinuity exists at 248.5 miles (400 km) depth, where velocity increases sharply due to a rearrangement of the atoms within olivine in a polymorphic transition into spinel structure, corresponding to an approximate 10 percent increase in density.

A major seismic discontinuity at 416 miles (670 km) could be either another polymorphic transition or a compositional change. This is the topic of many current investigations. Some models suggest that this boundary separates two fundamentally different types of mantle, circulating in different convection cells, whereas other models suggest that there is more interaction between rocks above and below this discontinuity.

The core-mantle boundary is one of the most fundamental on the planet, with a huge density contrast from 5.5 g/cm^3 above, to 10–11 g/cm^3 below, a contrast greater than that between rocks and air on the surface of the Earth. The outer core consists mainly of molten iron. An additional discontinuity occurs inside the core at the boundary between the liquid outer core and the solid, iron-nickel inner core.

Seismic waves can also be used to understand the structure of the Earth's crust. Andrija Mohorovičić, a Yugoslav seismologist, from Volosko in Croatia, noticed slow and fast arrivals from nearby earthquake source events. He proposed that some seismic waves traveled through the crust, some along the surface, and others were reflected off a deep seismic discontinuity between seismically slow and fast material at about 18.6 miles (30 km) depth. Geologists now recognize this boundary, called the Mohorovicic (or Moho) boundary, to be the base of the crust and use its seismically determined position to measure the thickness of the crust, typically between 6.2–43.5 miles (10–70 km).

GRAVITY ANOMALIES (POTENTIAL FIELD STUDIES)

Gravity anomalies are the difference between the observed value of gravity at a point and the theoretically calculated value of gravity at that point, based on a simple gravity model. The value of gravity at a point reflects the distribution of mass and rock units at depth, as well as topography. The average gravitational attraction on the surface is 32 feet per second squared (9.8 m/s^2), with one gravity unit (g. u.) being equivalent to one ten-millionth of this value. Another older unit of measure, the milligal, is equivalent to 10 gravity units. The range in gravity on the Earth's surface at sea level is about 50,000 g.u., from 32.09–32.15 feet per second squared (9.78–9.83 m/s^2). An adult human would weigh slightly more at the poles than at the equator because the Earth has a slightly larger radius at the equator than at the poles.

Geologically significant variations in gravity are typically only a few tenths of a gravity unit, so instruments that measure gravity anomalies must be very sensitive. Some gravity surveys use closely to widely spaced gravity meters on the surface, whereas others use observations of the perturbations of orbits of satellites.

The determination of gravity anomalies involves subtracting the effects of the overall gravity field of the Earth, accomplished by removing the gravity field at sea level (geoid), leaving an elevation-dependent gravity measurement. This measurement reflects a lower gravitational attraction with height and distance from the center of the Earth, as well as an increase in gravity caused by the gravitational pull of the material between the point and sea level. The free-air gravity anomaly is a correction to the measured gravity calculated using only the elevation of the point and the radius and mass of the Earth. A second correction, known as the Bouguer gravity anomaly, depends on the shape and density of rock masses at depth. Sometimes a third correction, known as the isostatic correction, is applied to gravity measurements. This applies when a load such as a mountain, sedimentary basin, or other mass is supported by mass deficiencies at depth, much like an iceberg floating lower in the water. There are several different mechanisms of possible isostatic compensation, however, and it is often difficult to know which mechanisms are important on different scales. Therefore this correction is often not applied.

Different geological bodies are typically associated with different magnitudes and types of gravity anomalies. Belts of oceanic crust thrust on continents (ophiolites) represent unusually dense material and are associated with positive gravity anomalies of up to several thousand g.u. Likewise, massive sulfide metallic ore bodies are unusually dense and are also associated with positive gravity anomalies. Salt domes, oceanic trenches, and mountain ranges all represent an increase in the amount of low-density material in the crustal column, and are therefore associated with increasingly negative gravity anomalies, with negative values of up to 6,000 g.u. associated with the highest mountains on Earth, the Himalayan chain.

GEOPHYSICS AND ISOSTACY

Isostacy is the principle of hydrostatic equilibrium applied to the Earth, referring to the position of the lithosphere essentially floating on the asthenosphere, similar to how low-density ice floats at a certain level on water, depending on the relative densities of the water and ice. Isostatic forces are of major importance in controlling the topography of the Earth's surface. There are several different models for how topography is supported, referred to as isostatic models. The simplest models have blocks of crust that are essentially floating as isolated blocks in a fluid substrate (the asthenosphere). Such blocks are free to migrate vertically and do not interact with neighboring blocks. There are two main variations of these simple isostatic models. In the Pratt model crustal blocks of different density are assumed to extend to a constant depth known as the depth of compensation, and the height of the topography varies inversely with the density of each block. Thus high-density oceanic crust resides at a lower level than lower-density continental crust. In the Airy model the level of isostatic compensation varies for each block, but the crustal layer is assumed to have a constant density. This way thick blocks have high topography and a thick root to compensate the topography, whereas thin crustal blocks have subdued topography. Both of these models are simplistic descriptions of a complex lithosphere, having been derived in the 1700s before an appreciation of plate tectonics. The Airy model is generally more applicable than the Pratt model, but the Airy model does not accommodate known variations in crustal density, such as that between continents and oceans.

Isostatic anomalies are variations in measured gravity values from those expected using an assumed isostatic model and depth of compensation. The anomaly indicates that the model used or the compensation depth assumed needs to be adjusted in the model.

See also ASTHENOSPHERE; CONVECTION AND THE EARTH'S MANTLE; EARTH; EARTHQUAKES; GEODESY; GEODYNAMICS; GEOID; GRAVITY, GRAVITY ANOMALY; MAGNETIC FIELD, MAGNETOSPHERE; MANTLE; PALEOMAGNETISM; PETROLEUM GEOLOGY; PLATE TECTONICS; REMOTE SENSING; SEISMOLOGY.

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geyser Geysers are springs in which hot water or steam sporadically or episodically erupts as jets from an opening in the surface, in some cases creating a tower of water hundreds of feet (tens of meters) high. Geysers are often marked on the surface by a cone of siliceous sinter and other minerals that precipitated from the hot water, known as geyser cones. Many also have deposits of thermophilic (heat-loving) bacteria that can form layers and mounds in stromatolitic buildups. Geysers form where water in pore spaces and cracks in bedrock gets heated by an underlying igneous intrusion or generally hot rock, causing it to boil and erupt, then the lost water is replaced by other water that comes in from the side of the system. In this way a circulation system is set up that in some cases is quite regular with a predictable period between eruptions. The most famous geyser in the world is Old Faithful in Yellowstone National Park, Wyoming, which erupts every 20 to 30 minutes.

Thermal springs in which the temperature is greater than that of the human body are known as hot springs. They are found in places where porous structures such as faults, fractures, or karst terrains channel meteoric water (derived from rain or snow) deep into the ground where it warms, and also where it can escape upward fast enough to prevent it from cooling by conduction to the surrounding rocks. Most hot springs, especially those with temperatures above 140°F (60°C), are associated with regions of active volcanism or deep magmatic activity, although some hot springs are associated with regions of tectonic extension without known magmatism. Active faulting is favored for the development of hot springs since the fluid pathways tend to become mineralized and closed by minerals that precipitate out of the hot waters, and the faulting is able to break repeatedly and reopen these closed passageways.

When cold, descending water heats up in a hot spring thermal system, it expands and the density of the water decreases, giving it buoyancy. Typical geothermal gradients increase about 120–140°F per mile (25–30°C per km) in the Earth, so for surface hot springs to attain temperatures of greater than 140°F (60°C), it is usually necessary for the water to circulate to at least two miles (two or three kilometers) depth. This depth may be less in volcanically active areas where hot magmas may exist at shallow crustal levels, reaching several hundred degrees at two miles (three kilometers) depth. Hot springs may boil when the temperatures of the waters reach or exceed 212°F (100°C), and if the rate of upward flow is fast enough to allow decompression. In these cases boiling water and steam may be released at the surface, sometimes forming geysers.

Hot springs are often associated with a variety of mineral precipitates and deposits, depending on the composition of the waters that come from the springs. This composition is typically determined by the type of rocks the water circulates through and is able to leach minerals from, with typical deposits including mounds of travertine, a calcium carbonate precipitate, siliceous sinters, and hydrogen sulfides.

Hot springs are common on the seafloor, especially around the oceanic ridge system where magma is located at shallow levels. The great pressure of the overlying water column on the seafloor elevates the boiling temperature of water at these depths, so that vent temperatures may exceed 572°F (300°C). Submarine hot springs often form 10-foot (several meter) or taller towers of sulfide minerals with black clouds of fine metallic mineral precipitates emanating from the hot springs. These systems, known as black smoker chimneys, host some of the most primitive known life-forms on Earth, some of which derive their energy from the sulfur and other minerals that come out of the hot springs rather than from sunlight.

Geysers and hot springs may be the surface outflows of hot waters that flow from deep within the

Beehive Geyser at Yellowstone National Park, Wyoming *(National Park Service)*

Earth. Many geysers and hot springs contain water that fell as rain, seeped into the Earth where it got heated, then rose again to the surface. Other hot springs and geysers have water that came from deeper levels in the Earth's crust, are known as hydrothermal fluids. Most heated subsurface waters contain dissolved minerals or other substances. Known as hydrothermal solutions, these waters are important because they dissolve, transport, and redistribute many elements in the Earth's crust and are responsible for the concentration and deposition of many ores, including many gold, copper, silver, zinc, tin, and sulfide deposits. These mineral deposits are known as hydrothermal deposits.

Hydrothermal solutions are typically derived from one or more sources, including fresh or saline groundwater, water trapped in rocks as they are deposited, water released during metamorphic reactions, or water released from magmatic systems. The minerals, metals, and other compounds dissolved in hydrothermal solutions often come from the dissolution of the rocks through which the fluids migrate or are released from magmatic systems. Hydrothermal solutions commonly form during the late stages of crystallization of a magmatic body, and these fluids contain many of the chemical elements that do not readily fit into the atomic structures of the minerals crystallizing from the magma. These fluids tend to be enriched in lead, copper, zinc, gold, silver tin, tungsten, and molybdenum. Many hydrothermal fluids are also saline, with the salts derived from leaching of country rocks. Saline solutions are much more effective at carrying dissolved metals than nonsaline solutions, so these hydrothermal solutions tend to be enriched in dissolved metals.

As hydrothermal solutions move up through the crust, they cool from as high as 1,112°F (600°C), and at lower temperatures the solutions cannot hold as much dissolved material. Therefore as the fluids cool, hydrothermal veins and ore deposits form, with different minerals precipitating out of the fluid at different temperatures. Some minerals may also precipitate out when the fluids come into contact with rocks of a certain composition, with a fluid-wall rock reaction.

GEOTHERMAL ENERGY IN REGIONS WITH GEYSERS

Geysers, hot springs, and fumaroles are associated with regions of elevated temperature at depth, and in some cases these high temperatures have been exploited for geothermal energy. Temperatures in the Earth generally increase downward at 90°–250°F (30°–140°C) per mile (68–212°F [20°–100°C] per km), following the geothermal gradient for the region. Some regions near active volcanic vents and deep-seated plutons have even higher geothermal gradients and are typified by abundant fumaroles and hot springs. These systems are usually set up when rising magma heats groundwater in cracks and pore spaces in rocks, and this heated water rises to the surface. Water from the sides of the system then moves in to replace the water that rose into hot springs, fumaroles, and geysers, and a natural hydrothermal circulation system is set up. The best natural hydrothermal systems are found in places where there are porous rocks and a heat source such as young magma.

Geothermal energy may be tapped by drilling wells, frequently up to several kilometers deep, into the natural geothermal systems. Geothermal wells that penetrate these systems commonly encounter water and less commonly steam at temperatures exceeding 572°F (300°C). Since water boils at 212°F (100°C) at atmospheric pressure and higher temperatures at higher pressures (being 300°C at a 1-km depth), the water can be induced to boil by reducing the pressure by bringing it toward the surface in pipes. For a geothermal well to be efficient, the temperatures at depth should be greater than 392°F (200°C). Turbines attached to generators are attached to the tops of wells, requiring about two kilograms of steam per second to generate each megawatt of electricity.

Some countries use geothermal energy to produce large amounts of electricity or heated water, with China, Hungary, Iceland, Italy, Japan, Mexico, and New Zealand leading the list. Still, the use of geothermal energy amounts to a very small but growing amount of the total electrical energy used by industrialized nations around the world.

See also BLACK SMOKER CHIMNEYS; ENERGY IN THE EARTH SYSTEM.

Gilbert, Grove K. (1843–1918) American *Geologist, Geomorphologist* Grove Gilbert is well known for his concept of graded streams. This concept maintains that streams always make channels and slopes for themselves either by cutting down their beds or by building them up with sediment so that over a period of time these channels will transport exactly the load delivered into them from above. Gilbert also explained the structure of the Great Basin as a result of extension, that is, individual "basin ranges" are the eroded upper parts of tilted blocks displaced along faults as "comparatively rigid bodies of strata."

Grove Karl Gilbert was born on May 6, 1843, in Rochester, New York, and graduated from the University of Rochester. In 1871 Gilbert joined the geographical survey of George M. Wheeler, a pioneering explorer and cartographer of the western United States. The Wheeler Survey was charged by the U.S.

Congress to map a portion of the United States west of the 100th meridian at a scale of eight miles to the inch, a task the Wheeler Survey and the similar King and Powell Surveys continued until 1879. Gilbert moved to the Powell Survey in 1874, mapping parts of the Rocky Mountain region. In 1879 the Wheeler and the King and Powell surveys were reorganized to form the United States Geological Survey.

In 1877 Gilbert published an important geological monograph *The Geology of the Henry Mountains.* As a result of his studies on the Henry Mountains (1875–76), he was the first to establish that intrusive bodies are capable of deforming the host rock, and he illustrated his monograph with examples of this process. He insisted that the Earth's crust is "as plastic in great masses as wax is in small." Unfortunately he exaggerated the fluidity of magma. Gilbert was conscientious in giving credit to those who deserved it but paid no attention when it was given to him. Gilbert's report also introduced new concepts of erosion and river and stream system development that are commonly used in modern theories of physical geology.

In 1879 Gilbert was a senior geologist with the United States Geological Survey, and from 1889 to 1892, he was the chief geologist. During this time he completed and published several important studies of the American West ranging from the structure and origin of the mountain ranges to the processes involved in the evolution of the stream systems. In 1890 he published his analysis of the Pleistocene Lake Bonneville as the first monograph of the U.S. Geological Survey. A small remnant of Lake Bonneville is preserved as the Great Salt Lake, in Utah. This pluvial lake covered much of the Great Basin region in Utah, Idaho, and Nevada. Lake Bonneville formed about 32,000 years ago, and much of it was drained suddenly through Red Rock Pass in Idaho 16,800 years ago. This catastrophic event occurred when the lake flowed over a natural dam formed by coalesced alluvial fans at Red Rock Pass, and rapidly eroded and downcut the fans as the lake waters rushed through, dropping the lake level by 350 feet (105 m). The flood from this event was a huge geologic event, releasing about 1,000 cubic miles (4,168 km^3) of water in the first few weeks and lasting about a year. Before the catastrophic draining, the lake had a surface area similar to that of Lake Michigan (19,691 square miles, or 51,000 km^2) and up to 1,000 feet (305 m) deep. The lake dried up further starting 14,000 years ago, as the glaciers retreated from North America and the climate dried, leaving a few remnants including Great Salt Lake, Little Salt Lake, Sevier Lake, and Rush Lake for the past 12,000 years.

Grove Gilbert is most remembered for his major contributions to the field of geomorphology and his observations on landscape evolution, erosion, river incision, and sedimentation. Gilbert was awarded the Wollaston Medal in 1990, the highest award given by the Geological Society of London.

See also GEOMORPHOLOGY; NORTH AMERICAN GEOLOGY; SEDIMENTARY ROCK, SEDIMENTATION.

FURTHER READING

Gilbert, G. K. "Report on the Geology of the Henry Mountains-Reprint of 1880 Paper." *Earth Science* 31 (1976): 68–74.

glacier, glacial systems Any permanent body of ice (recrystallized snow) that shows evidence of gravitational movement is known as a glacier. Glaciers are an integral part of the cryosphere, that portion of the planet where temperatures are so low that water exists primarily in the frozen state. Most glaciers presently reside in the polar regions and at high altitudes. At several times in Earth's history, however, glaciers have advanced deeply into midlatitudes, and the climate of the entire planet was different. Some models suggest that at one time ice covered the entire surface of the Earth, a state referred to as the "snowball Earth." Glaciers are dynamic systems, always moving under the influence of gravity and changing drastically in response to changing global climate systems. Thus, changes in glaciers may reflect coming changes in the environment.

Several types of glaciers exist. Mountain glaciers form in high elevations and are confined by surrounding topography, such as valleys. Specific types of mountain glaciers include cirque glaciers, valley glaciers, and fjord glaciers. Piedmont glaciers are fed by mountain glaciers but terminate on open slopes beyond the mountains. Some piedmont and valley glaciers flow into open water, bays, or fjords, and are known as tidewater glaciers. Ice caps form dome-shaped bodies of ice and snow over mountains and flow radially outward. Ice sheets are huge, continent-sized masses of ice that presently cover Greenland and Antarctica and are the largest glaciers on Earth, making up about 95 percent of all the glacier ice on the planet. If global warming were to continue to melt the ice sheets, sea level would rise by 230 feet (66 m). A polar ice sheet covers Antarctica. This ice sheet consists of two parts that meet along the Transantarctic Mountains. The Antarctic ice sheet contains shelves (thick glacial ice that floats on the sea), which form many icebergs by breaking and separating in a process called calving and which move northward into shipping lanes of the Southern Hemisphere.

Polar glaciers form where the mean average temperature lies below freezing, and these glaciers have little or no seasonal melting because the temperature does not increase sufficiently. Other glaciers, called temperate glaciers, have seasonal melting periods, when the temperature throughout the glacier may be at the pressure melting point (when the ice can melt at that pressure and both ice and water coexist). All glaciers form above snow line, the lower limit at which snow remains year-round, located at sea level in polar regions and at 5,000–6,000 feet (1,525–1,830 m) at the equator (Mount Kilamanjaro in Tanzania has glaciers, although these are melting rapidly).

Glaciers are sensitive indicators of climate change and global warming, shrinking in times of warming and expanding in times of cooling. Glaciers may be thought of as the "canaries in the coal mine" for climate change.

The Earth has experienced at least three major periods of long-term frigid climate and ice ages, interspersed with periods of warm climate. The earliest well-documented ice age is the period of the "snowball Earth" in the Late Proterozoic from about 710–650 million years ago, although there is evidence of several earlier glaciations. Beginning about 350 million years ago the Late Paleozoic saw another ice age lasting about 100 million years until 250 million years ago. The planet entered the present ice age about 55 million years ago. Varied underlying causes of these different glaciations include anomalies in the distribution of continents and oceans and associated currents, variations in the amount of incoming solar radiation, and changes in the atmospheric balance between the amount of incoming and outgoing solar radiation.

FORMATION OF GLACIERS

Glaciers form mainly by the accumulation and compaction of snow, and are deformed by flow under the influence of gravity. When snow falls it is porous, and with time the pore spaces close by precipitation and compaction. When snow first falls, it has a density of about 1/10th that of ice; after a year or more the density is transitional between snow and ice, and it is called firn. After several years the ice reaches a density of 0.9 g/cm^3, and it flows under the force of gravity. At this point glaciers are considered to be metamorphic rocks, composed of the mineral ice.

The mass and volume of glaciers constantly change in response to the seasons and to global climate variations. The mass balance of a glacier is determined by the relative amounts of accumulation and ablation (mass loss through melting and evaporation or calving). Some years see a mass gain leading to glacial advance, whereas some periods have a mass loss and a glacial retreat (the glacial front or terminus shows these effects).

Glaciers have two main zones, best observed at the end of the summer ablation period. The zone of accumulation, found in the upper parts of the glacier, remains covered by the remnants of the previous winter's snow. Below this the zone of ablation is characterized by older, dirtier ice from which the previous winter's snow has melted. An equilibrium line, marked by where the amount of new snow exactly equals the amount that melts that year, separates these two zones.

MOVEMENT OF GLACIERS

When glacial ice becomes thick enough, it begins to flow and deform under the influence of gravity. The thickness of the ice must be great enough to overcome the internal forces that resist movement, which depend on the temperature of the glacier. The thickness at which a glacier starts flowing also depends on the steepness of the slope on which it flows—thin glaciers can move on steep slopes, whereas to move across flat surfaces, glaciers must become very thick. The flow is by creep, or deformation of individual mineral grains. This creep leads to the preferential orientation of mineral (ice) grains, forming foliations and lineations, much the same way as in other metamorphic rocks.

Some glaciers develop a layer of meltwater at their base, allowing basal sliding and surging to occur. Where glaciers flow over ridges, cliffs, or steep slopes, their upper surface fails by cracking, forming large, deep crevasses that can extend to 200 feet (65 m) deep. A thin blanket of snow can cover these crevasses, making dangerous conditions for travelers on the ice.

Ice in the central parts of valley glaciers moves faster than at the sides because of frictional drag against the valley walls on the side of the glacier. Similarly, a profile with depth into the glacier would show that it moves the slowest along its base and faster internally and along its upper surfaces. When a glacier surges, the ice in the base may temporarily move as fast as the ice in the center and on top. This is because during surges, frictional resistance is reduced, and the glacier essentially rides on a cushion of meltwater along the glacial base. During meltwater-enhanced surges, glaciers may advance by as much as several kilometers in a year. Events like this may happen in response to climate changes.

GLACIATION AND GLACIAL LANDFORMS

Glaciation is the modification of the land's surface by the action of glacial ice. When glaciers move over the land's surface, they plow up the soils, abrade and file down the bedrock, carry and transport the sedimentary load, steepen valleys, then leave thick deposits of glacial debris during retreat.

In glaciated mountains a distinctive suite of landforms results from glacial action. Glacial striations are scratches on the surface of bedrock, formed when a glacier drags boulders across the bedrock surface. Rouche moutonnées and other asymmetrical landforms are made when the glacier plucks pieces of bedrock from a surface and carries them away. The step faces in the direction of transport. Cirques are bowl-shaped hollows that open downstream and are bounded upstream by a steep wall. Frost wedging, glacial plucking, and abrasion all work to excavate cirques from previously rounded mountaintops. Many cirques contain small lakes called tarns, which are blocked by small ridges at the base of the cirque. Cirques continue to grow during glaciation, and where two cirques form on opposite sides of a mountain, a ridge known as an arete forms. A steep-sided mountain known as a horn forms where three cirques meet. The Matterhorn of the Swiss Alps is an example of a glacial carved horn.

Valleys that have been glaciated have a characteristic U-shaped profile, with tributary streams entering above the base of the valley, often as waterfalls. In contrast, streams generate V-shaped valleys. Fjords are deeply indented glaciated valleys partly filled by the sea. In many places that were formerly overlain by glaciers, elongate streamlined forms known as drumlins occur. These are both depositional features (composed of debris) and erosional (composed of bedrock).

Terminal moraines are ridgelike accumulations of drift deposited at the farthest point of travel of a glacier's terminus. They may be found as depositional landforms at the bases of mountain or valley glaciers, marking the locations of the farthest advance of that particular glacier, or may be more regional, marking the farthest advance of a continental ice sheet. There are several different categories of terminal moraines, some related to the farthest advance during a particular glacial stage, and others referring to the farthest advance of a group of or all glacial stages in a region. Continental terminal moraines are typically succeeded poleward by a series of recessional moraines marking temporary stops in the glacial retreat or even short advances during the retreat. They may also mark the boundary between glacial outwash terrain toward the equator, and knob and kettle or hummocky terrain toward the pole from the moraine. The knob and kettle terrain is characterized by knobs of outwash gravels and sand separated by depressions filled with finer material. Many of these kettle holes were formed when large blocks of ice were left by the retreating glacier, and the ice blocks melted later leaving large pits where the ice once was. Kettle holes are typically filled with lakes, and many regions characterized by many small lakes have a recessional kettle hole origin.

GLACIAL TRANSPORT

Glaciers transport enormous amounts of rock debris, including large boulders, gravel, sand, and fine silt. The glacier may carry this at its base, on its surface, or internally. Glacial deposits are characteristically poorly sorted or nonsorted, with large boulders next to fine silt. Most of a glacier's load is concentrated along its base and sides, because in these places plucking and abrasion are most effective.

Active ice deposits till as a variety of moraines, which are ridgelike accumulations of drift deposited on the margin of a glacier. A terminal moraine is the farthest point of travel of the glacier's terminus. Glacial debris left on the glaciers' sides forms lateral moraines, whereas where two glaciers meet, their moraines merge into a medial moraine.

Rock flour is a general name for the deposits at the base of glaciers, where they are produced by crushing and grinding by the glacier to make fine silt and sand. *Glacial drift* is a general term for all sediment deposited directly by glaciers, or by glacial meltwater in streams, lakes, and the sea. Till is a type of glacial drift deposited directly by the ice and characterized by a nonsorted random mixture of rock fragments. Glacial marine drift is sediment deposited on the seafloor from floating ice shelves or bergs and may include many isolated pebbles or boulders that were initially trapped in glaciers on land, then floated in icebergs that calved off from tidewater glaciers. These rocks melted out while over open water and fell into the sediment on the sea bottom. These isolated dropstones are often one of the hallmark signs of ancient glaciations in rock layers that geologists find in the rock record. Stratified drift is deposited by meltwater and may include a range of sizes, deposited in different fluvial or lacustrine environments.

Glacial erratics are glacially deposited rock fragments with compositions different from underlying rocks. In many cases the erratics are composed of rock types that do not occur in the area where they are located but are normally found only hundreds or thousands of miles away. Many glacial erratics in the northern United States can be shown to have come from parts of Canada. Some clever geologists have used glacial erratics to help them find mines or rare minerals that they have located in an isolated erratic—they used their knowledge of glacial geology to trace the boulders back to their sources following the orientation of glacial striations in underlying rocks. Recently diamond mines were discovered in northern Canada (Nunavut) by tracing diamonds found in glacial till back to their source.

Sediment deposited by streams washing out of glacial moraines, known as outwash is typically deposited by braided streams. Many of these form on broad outwash plains. When glaciers retreat, the load is diminished, and a series of outwash terraces may form.

ICE CAPS

Glaciers are any permanent body of ice (recrystallized snow) that shows evidence of gravitational movement. Ice caps form dome-shaped bodies of ice and snow over mountains, and flow radially outward. They cover high peaks of some mountain ranges, such as parts of the Kenai and Chugach Mountains in Alaska, the Andes, and many in the Alpine-Himalayan system. Ice caps are relatively small, fewer than 20,000 square miles (50,000 km^2), whereas ice sheets are similar but larger. Ice sheets are continent-sized masses of ice that presently cover Greenland and Antarctica. About 95 percent of all the glacier ice on the planet exists as ice sheets. If global warming continues to melt the ice sheets, the sea level will rise by 230 feet (70 m). Antarctica is covered by an ice cap that covers the entire continent, with only peaks of the Transantarctic mountains poking through in the center of the continent. This ice cap is surrounded by many ice shelves that are collapsing and forming many icebergs that move northward into the shipping lanes, where they pose hazards to ships.

Global sea levels are currently rising, partly as a result of the melting of the Greenland and Antarctica ice sheets. The Earth is presently in an interglacial stage of an ice age, and sea levels have risen nearly 400 feet (120 m) since the last glacial maximum 20,000 years ago, and about six inches (15 cm) in the past 100 years. The rate of sea-level rise seems to be accelerating and may presently be as much as an inch (2.5 cm) every 10 years. If all the glaciers melted in Greenland and Antarctica, then sea level would rise globally by 230 feet (70 m), inundating most of the world's major cities and submerging large parts of the continents under shallow seas. The coastal regions of the world are densely populated and experiencing rapid population growth. Approximately 100 million people presently live within 3.2 feet (1 m) of the present-day sea level. If sea level were to rise rapidly and significantly, we would experience an economic and social disaster of a magnitude never experienced by the civilized world. Many areas would flood permanently or become subjected to inundation by storms, beach erosion would accelerate, and water tables would rise.

The Greenland and Antarctic ice sheets have significant differences that cause them to respond differently to changes in air and water temperatures. The Antarctic ice sheet is about ten times as large as the Greenland ice sheet, and since it sits on the South Pole, Antarctica dominates its own climate. The surrounding ocean is cold even during summer, and much of Antarctica is a cold desert with low precipitation rates and high evaporation potential. Most meltwater in Antarctica seeps into underlying snow and simply refreezes, with little running off into the sea. Antarctica hosts several large ice shelves fed by glaciers moving at rates of up to a thousand feet per year. Most ice loss in Antarctica is accomplished through calving and basal melting of the ice shelves at rates of 10–15 inches (25–38 cm) per year.

In contrast, Greenland's climate is influenced by warm North Atlantic currents and by its proximity to other landmasses. Climate data measured from ice cores taken from the top of the Greenland ice cap show that temperatures have varied significantly in cycles of years to decades. Greenland also experiences significant summer melting and abundant snowfall, and has few ice shelves. Its glaciers move quickly at rates of up to miles per year. These fast-moving glaciers can drain a large amount of ice from Greenland in relatively short time spans.

The Greenland ice sheet is thinning rapidly along its edges, having lost an average of 15–20 feet (4.5–6 m) in the past decade. In addition, tidewater glaciers and the small ice shelves in Greenland are melting at an order of magnitude faster than the Antarctic ice sheets, with rates of melting between 25–65 feet (7–20 m) per year. About half of the ice lost from Greenland is through surface melting that runs off into the sea. The other half is through calving of outlet glaciers and melting along the tidewater glaciers and ice-shelf bases.

These differences between the Greenland and Antarctic ice sheets lead them to play different roles in global sea-level rise. Greenland contributes more to the rapid short-term fluctuations in sea level, responding to short-term changes in climate. In contrast, most of the world's water available for raising sea level is locked in the slowly changing Antarctic ice sheet. Antarctica contributes more to the gradual, long-term sea-level rise.

ICEBERGS AND SEA ICE

Calving is a process in which large pieces of ice break off from the fronts of tidewater glaciers, ice shelves, or sea ice. Typically, the glacier cracks like an explosion, then a large chunk of ice splashes into the water, detaching from the glacier. Calving causes glaciers to retreat rapidly. Ice that has broken off an ice cap, polar sea, or calved off a glacier and is floating in open water is known as sea ice or, more commonly, icebergs. Presenting a serious hazard to ocean traffic and shipping lanes, icebergs have sunk numerous vessels, including the ill-fated RMS *Titanic* in 1912, killing 1,503. Icebergs float on the surface, but between 81 and 89 percent of the ice is submerged. The water level at which sea ice floats depends on the

Calving in Glacier Bay National Park, Alaska *(Scott Kapich, Shutterstock, Inc.)*

exact density of the ice, as determined by the total amount of air bubbles trapped in the ice and how much salt got trapped there during freezing.

Four main categories of sea ice may break off from larger glaciers, ice caps, or ice shelves to form many icebergs. The first comes from ice that formed on polar seas in the Arctic Ocean and around Antarctica. The ice that forms in these regions is typically about 10–15 feet (3–4 m) thick. Antarctica becomes completely surrounded by this sea ice every winter, and the Arctic Ocean is typically about 70 percent covered in the winter. During summer many passages open up in this sea ice, but during winter they reclose, forming pressure ridges of ice that may be 50–100 feet (up to tens of meters) high. Recent observations suggest that the sea ice in the Arctic Ocean is thinning dramatically and rapidly, and may soon disappear altogether. The icecap over the Arctic Ocean rotates clockwise, in response to the spinning of the Earth. This spinning is analogous to putting an ice cube in a glass, and slowly turning the glass. The ice cube will rotate more slowly than the glass, because it is decoupled from the edge of the glass. About one-third of the ice is removed every year by the East Greenland current. This ice then moves south and becomes icebergs, and thus hazards to shipping in the North Atlantic.

A second group of sea ice forms as pack ice in the Gulf of St. Lawrence, along the southeast coast of Canada; in the Bering, Beaufort, and Baltic Seas; in the Seas of Japan and Okhotsk; and around Antarctica. Pack ice builds up especially along the western sides of ocean basins, where cold currents are more common. Occasionally, during cold summers, pack ice persists throughout the summer.

Pack ice is hazardous when it becomes so extensive that it effectively blocks shipping lanes, or when leads (channels) into the ice open and close, forming pressure ridges that become too thick to penetrate with ice breakers. Ships attempting to navigate through pack ice have become crushed when leads close, and the ships are trapped. Pack ice has terminated or resulted in disaster for many expeditions to polar seas, most notably Sir John Franklin's expedition in 1845 in the Canadian arctic and Robert F. Scott's expedition from 1901 to 1904 to Antarctica. Pack ice also breaks up, forming many small icebergs, but because these are not as thick as icebergs of other origins, they do not present as significant a hazard to shipping.

Pack ice also presents hazards when it drifts into shore, usually during spring breakup. With significant winds pack ice can pile up on flat shorelines and accumulate in stacks up to 50 feet (15 m) high. The tremendous force of the ice is enough to crush shoreline wharves, docks, buildings, and boats. Pack ice blown ashore also commonly pushes up high piles of gravel and boulders that may be 35 feet (10.5 m) high in places. These ridges are common around many of the Canadian Arctic islands and mainland. Ice that forms initially attached to the shore presents another type of hazard. If it breaks free and moves away from shore, it may carry with it significant quantities of shore sediment, causing rapid erosion of beaches and shore environments.

Pack ice also forms on many high-latitude lakes, and the freeze-thaw cycle causes cracking of the lake ice. When lake water rises to fill the cracks, the ice cover on the lake expands and pushes over the shoreline, causing damage to any structures built along the shore. This is a common problem on many lakes in northern climates and leads to widespread damage to docks and other lakeside structures.

Icebergs derived from glaciers present the greatest danger to shipping. In the Northern Hemisphere most icebergs calve off glaciers in Greenland or Baffin Island, then move south through the Davis Strait into shipping lanes in the North Atlantic off Newfoundland. Some icebergs calve off glaciers adjacent to the Barents Sea, and others come from glaciers in Alaska and British Columbia. In the Southern Hemisphere most icebergs come from Antarctica, though some come from Patagonia, the southern tip of South America.

Once in the ocean icebergs drift with ocean currents, but the Coriolis force deflects them to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. Most icebergs are about 100 feet to 300 feet (30.5–91.5 m) high, and up to about 2,000 feet (609.5 m) long. In March 2000 a huge iceberg broke off the Ross Ice Shelf in Antarctica. This berg was roughly the size of the state of Delaware, with an area of 4,500 square miles (11,655 km^2) and rising 205 feet (62.5 m) out of the water. Icebergs in the Northern Hemisphere pose a greater threat to shipping, as those from Antarctica are too remote and rarely enter shipping lanes. Ship collisions with icebergs have resulted in numerous maritime disasters, especially in the North Atlantic on the rich fishing grounds of the Grand Banks off the coast of Newfoundland.

Satellites now track icebergs, and ships receive updated information about their positions to avoid disastrous collisions. Radio transmitters are placed on larger icebergs to monitor their locations more closely; many ships now carry more sophisticated radar and navigational equipment that helps track the positions of large icebergs and the ship, to avoid collision.

Icebergs also pose a serious threat to oil-drilling platforms and seafloor pipelines in high-latitude seas. Some precautions have been taken, such as building seawalls around near-shore platforms, but not enough planning has gone into preventing an iceberg from colliding with and damaging an oil platform or from one being dragged across the seafloor and rupturing a pipeline.

See also CLIMATE; CLIMATE CHANGE; ICE AGES; SUPERCONTINENT CYCLES.

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global warming The term *global warming* generally refers to the phenomenon whereby the planet has been warming dramatically over the past century, whereas the more encompassing term *climate change* refers to longer-term changes. Most scientists suggest that human contributions to climate change have been accelerating to critical levels as the world becomes increasingly industrialized. Much of what is known about these short-term climate changes has been described in a report called *Climate Change 2007: The Physical Science Basis,* issued in late 2007 by the Intergovernmental Panel on Climate Change (IPCC), an international group of hundreds of scientists who have analyzed all available data, assessed the causes of these recent, short-term changes to the global climate, and made predictions of what the climate of the Earth may look like at various times in the future. Much of the information in this report is based on the findings of the IPCC.

Eleven of the 12 years between 1996 and 2006 were the warmest on record since weather-recording instruments were widely used starting in 1850. The temperature rate increase seems to be increasing, with polar areas affected more than equatorial regions. Sea levels are also rising at an increasing rate. Between 1961 and 1993 global sea level was rising at a rate of 0.05–0.09 inches per year (0.13–0.23 cm/yr), and since 1993 they have been rising at 0.09–0.11 inches per year (0.24–0.28 mm/yr). Some of the sea level rise is due to melting glaciers, ice caps, and snow, and some is from thermal expansion of ocean water as the water warms. Glaciers are shrinking in both the northern and southern hemispheres, and the ice caps on the Arctic Ocean and over parts of Antarctica are shrinking rapidly.

Global precipitation patterns are observably changing on the century scale, with much of eastern North and South America, northern Europe, and north and central Asia seeing increased rainfall, but other areas such as the Sahel, Mediterranean, southern Africa, and southern Asia are experiencing decreased precipitation. On a global scale areas experiencing drought or less precipitation are greater than areas receiving greater precipitation.

TEMPERATURE VARIATIONS DURING THE PAST 1,000 YEARS

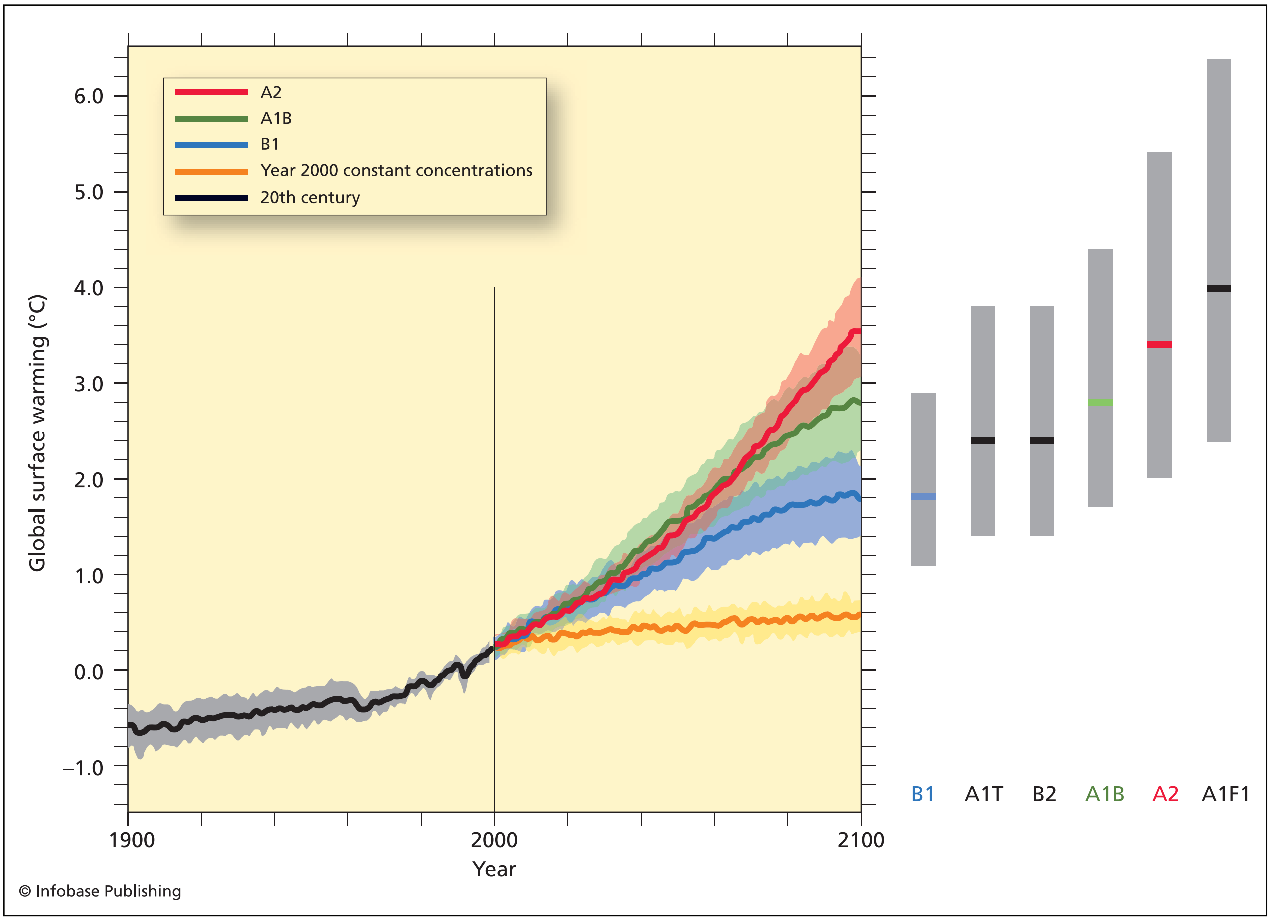
Understanding changes in the Earth's climate in the past 100–200 years, or the slightly longer interval extending back through the last glacial interval, rely on several types of data. Instrumental records of Earth's climate extend back to about the year 1850, when recording devices were put into widespread use. Long cores of ice obtained from Greenland and other locations are also widely used to measure past climate conditions, with this record extending back for about 650,000 years.

The IPCC issued the following statement in November 2007:

> Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. Global atmospheric concentrations (of greenhouse gases) have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial levels. The global increases in carbon dioxide concentration are due primarily to fossil fuel use and land-use change, while those of methane and nitrous oxide are primarily due to agriculture.

This bold and controversial statement was based on rigorous analysis of data from the past 1,000 years, showing that temperatures remained fairly steady at about 0–0.5 degrees below the 1990 average value from the year 1000 to about 1910, then began a sharp upward turn that flattened off for a short time in the 1950s, and has turned sharply up again since about 1976. Temperatures are now about 0.5–1.0

Mother polar bear and cub, threatened by global warming *(Keith Levit, Shutterstock, Inc.)*



Plot of the average global temperature variations on the planet in the past 1,000 years and what different models predict the temperature will be by 2100. All models show a predicted temperature rise, ranging between 1.5 and 5.5 degrees. *(Data from IPCC 2007)*

degrees above the 1990 value, and expected to rise 2–5 degrees above this value by 2100.

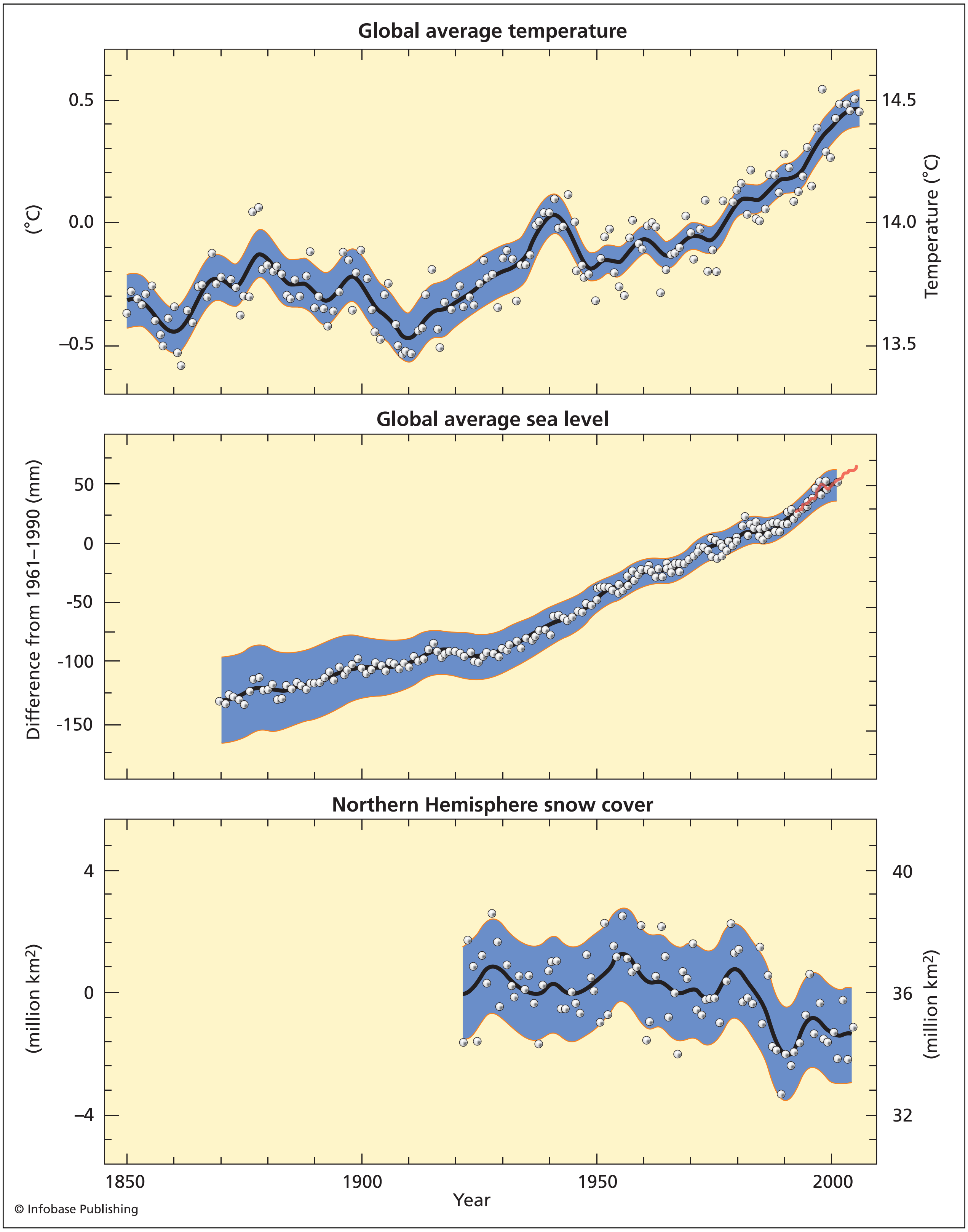
To measure global average temperatures groups of meteorologists, such as the World Meteorological Organization (WMO) and the Global Climate Observing System (GCOS), have a large number of observation points on the continents, which are then gridded into equal areas to assign a temperature for each box in the grid. Observations from satellites are widely used where local observations are not available and for calibrating the models. Local effects, such as any urban heat island effect from cities, are accounted for in these types of model. With rapid improvements in computer modeling it has been possible to make more and more detailed and accurate models for the Earth.

OBSERVED SHORT-TERM CLIMATE CHANGES AND THEIR EFFECTS

Instrumental and ice core records show that several components of the atmosphere and surface have significant changes in the recorded climate history. First, the concentration of greenhouse gases such as carbon dioxide has increased dramatically since 1850, causing an increase in the atmospheric absorption of outgoing radiation and warming the atmosphere. Aerosols, microscopic droplets or airborne particles, have also increased, and these have reflected and absorbed incoming solar radiation.

The most obvious change in the short-term climate is the increase in temperature of the atmosphere and sea surface. The period between 1995 and 2006 ranks among the hottest on record since instrumental records have been in widespread use since 1850, containing 11 of the 12 hottest years recorded. Moreover, the rate of temperature rise has increased each decade since 1850. The total temperature increase since 1850 is estimated by the IPCC to be 1.4°F (0.76°C). Measurements of the atmospheric water vapor indicate it is increasing with increasing temperature of the atmosphere, although such measurements extend back only to the mid-1980s.

Sea level has been rising at about 0.07 inches per year (0.18 cm/yr) since 1961, and at 0.12 inches per year (0.31 cm/yr) since 1993. The temperature of the oceans to a depth of 1.9 miles (3 km) has been increasing since at least 1961, with seawater absorbing most (~ 80 percent) of the heat energy associated with global warming. This increase in seawater temperature is causing the water to expand, contributing to sea-level rise. Also contributing to sea-level rise is a dramatic melting of mountain glaciers in both the



Graphs of global average temperature, sea level, and snow cover for the past 160 years *(Data from IPCC 2007)*

Spruce killed by spruce bark beetle near Homer, Alaska *(Peter Essick/Aurora/Getty Images)*

Northern and the Southern Hemispheres. Changes in the ice caps on Greenland and Antarctica show an increased outflow of glacial ice and meltwater, so melting of the polar ice caps is very likely contributing to the measured sea-level rise. Both of these ice caps show significant thinning, much due to increased melting, but some (especially on Greenland) due also to decreased snowfall.

Many specific regions of the planet are showing dramatic changes in response to the global average warming surface conditions. For instance, the surface temperatures measured in the Arctic have been increasing at about twice the global rate for the past 100 years, although some fluctuations on a decadal scale have been observed as well. The sea ice that covers the Arctic Ocean may be on the verge of collapse, as the sea ice thins and covers a smaller area each year. Since 1978 the Arctic sea ice has diminished in aerial extent by 2.7 percent each decade. On land in Arctic regions the thick permafrost layer is also warming, by 4–5°F (~3°C), and a total decrease in the area covered by permafrost since 1900 is estimated to be about 7 percent. Permafrost locks a huge amount of peat and carbon into a closed system, so there are fears outlined in the IPCC report that the melting of the permafrost layer may release large amounts of carbon into the atmospheric system. The sea ice around Antarctica shows greater variations on interannual scales and no longer-term trends are yet discernible. Much of the Antarctic region is isolated from other parts of the global climate belt, so overall it shows less change than northern polar regions.

Precipitation patterns across much of the planet are changing as a result of global warming. Observations from 1900 to 2007 show long-term drying and potential desertification over parts of the sub-Saharan Sahel, the Mediterranean region, parts of southern Asia, and much of southern Africa. Deeper and longer droughts have been occurring over larger areas since the 1970s, and some of these conditions can be related to changes in ocean temperature, wind patterns, and loss of snow cover. Westerly winds in the mid latitudes have become stronger in both the Northern and the Southern Hemispheres since the 1960s.

Weather extremes show an increase in frequency, including heavy precipitation events over land, as well as heat waves and extreme temperatures over land. Many studies suggest that oceanic cyclones or hurricanes may also be becoming stronger and more frequent, but some decadal variations in oceanic cyclones may also complicate determination of these trends. Most studies support an increase in tropical cyclone activity since the 1970s over the North Atlantic, and relate this to the increase in sea surface temperatures.

CAUSES OF SHORT-TERM CLIMATE CHANGE

The IPCC issued new reports, *Climate Change 2007,* in 2007 revealing that concentrations of some greenhouse gases have increased dramatically as a result of human activities, mostly starting with the early industrial revolution around 1750 and accelerating in the late industrial revolution around 1850. The greenhouse gases that show the most significant increases are carbon dioxide, methane, and nitrous oxide. Carbon dioxide (CO_2), the most significant anthropogenic greenhouse gas, is produced mainly by burning fossil fuels such as coal, oil, and gasoline. The atmospheric concentrations of CO_2 have increased from a preindustrial revolution level of 280 parts per million (ppm) in the atmosphere to a present (2005) level of 379 ppm, far exceeding the natural range (180–300 ppm) measured over the past 650,000 years, but CO_2 levels have been higher in the geological past for reasons related to global volcanism, supercontinent cycles, and the like that operate on longer timescales than the changes measured since the industrial revolution. Despite significant variations on a year-to-year basis, the rate of CO_2 increase in concentration in the atmosphere has been accelerating over the past 10 years.

Methane in the atmosphere has increased in concentration from a pre–industrial revolution value of about 715 parts per billion (ppb) to 1,774 ppb in 2005. Methane is produced predominantly in agricultural production and also in burning fossil fuels. The rapid increase in atmospheric methane is, like carbon dioxide, well beyond the natural range (320–790 ppm) of the past 650,000 years. Nitrous oxide is released by agricultural activities and is a greenhouse gas. Its concentration has increased in the atmosphere from a pre–industrial revolution level of 270 ppb to 319 ppb in 2005.

Scientists on the IPCC estimate that the total increase in heating of the atmosphere due to anthropogenic increases in greenhouse gases since the start of the industrial revolution in 1750 is greater than other effects, and the rate of planet warming is now faster than any experienced in the past 10,000 years. *Radiative forcing* is the net change in downward minus the upward irradiance at the tropopause, caused by a change in an external driver such as a change in greenhouse gas concentration. The radiative forcing caused by the change in CO_2 between 1995 and 2005 is estimated to be about 20 percent, the largest amount in the past 200 years. The way to counteract this is to enforce climate treaties such as the Kyoto Protocols, which call for a reduction in CO_2 emissions; through the installation of scrubbers and other cleansing technologies on factories and power plants; and increasing the fuel efficiency of cars.

Some of the warming caused by increases in greenhouse gases may be counteracted by an increase in aerosols, small airborne solid or liquid particles, which may have a cooling effect. Aerosols include particles such as sulfate, organic carbon, black carbon, nitrates, and dust. As the climate warms, more and more dust is being picked up from regions undergoing increased aridness and desertification such as the fringes of the Gobi desert and the Sahara. This dust gets emplaced high into the atmosphere, where it may reside some time and may actually have a small cooling effect.

THE GREENHOUSE EFFECT

The term *greenhouse effect* refers to the Earth's climate as being sensitive to the concentrations of certain gases in the atmosphere. The concept was first coined by French physicist Edme Mariotte (1620–84) in 1681, who noted that light and heat from the Sun easily pass through a sheet of glass, but that heat from candles and other sources does not. This concept was then extended by French mathematician and physicist Joseph Fourier in 1824 to the atmosphere by noting that heat and light from the Sun can pass from space through the atmosphere, but heat radiated back to the atmosphere from Earth may get trapped by some of the atmospheric gases, just like the heat from a candle is partly blocked by the glass pane. Then in 1861 Irish physicist John Tyndall (1820–93) identified that the molecules of water (H_2O) and carbon dioxide (CO_2) were mainly responsible for the absorption of heat radiated back from Earth, and that other atmospheric gases such as nitrogen and oxygen did not play a role in this effect. Tyndall noted that simple changes in the concentrations of CO_2 and H_2O could alternately cool and heat the atmosphere, producing "all the mutations of climate which the researches of geologists reveal." The next step in understanding the greenhouse effect came from the work of Swedish physicist Svante Arrhenius in 1896, who calculated that a 40 percent increase or decrease in the atmospheric concentration of CO_2 could cause the advance and/or retreat of continental glaciers, triggering the glacial and interglacial ages. Much later a change in the atmospheric CO_2 of this magnitude was documented in cores of the Greenland ice sheet, as predicted by Arrhenius. Carbon dioxide can vary naturally in the atmosphere through a variety of driving mechanisms, including changes in volcanism, erosion and plate tectonics, and ocean-atmosphere interactions. The modern concept of linking greenhouse gases with the burning of fossil fuels was formulated by British steam engineer and amateur meteorologist Guy Stewart Callendar (1898–1964) in 1938, who calculated that a doubling of atmospheric CO_2 by burning fossil fuels would cause an average global temperature increase of about 3°F (2°C), with more heating at the poles. Callendar made prescient predictions that humans are changing the composition of the atmosphere at a rate that is "exceptional" on geological timescales, and he sought to understand what effects these changes might have on climate. His prediction was that the "principal result of increasing carbon dioxide will be a gradual increase in the mean temperature of the colder regions of the Earth." These predictions were first confirmed in 1947 when Ahlmann reported a 1–2°F (1.3°C) increase in the average temperature of the North Atlantic sector of the Arctic. However, at this time the nature of the complex interactions of the carbon cycle and exchange of CO_2 in the atmosphere-ocean system was not well understood, and many scientists attributed the entire temperature rise to human production of greenhouse gases. Later studies of ocean-atmosphere relationships, and biogeochemistry, showed more complex relationships. Later in the 1970s effects of aerosols in the atmosphere, principally to reflect solar radiation to space and cooling the Earth, began to be appreciated as another component of the greenhouse effect. The current state of knowledge of the complex physical, chemical, biological, and other processes associated with the greenhouse effect are described in the IPCC's *Climate Change 2007*.

COMPARISON OF SHORT-TERM CLIMATE CHANGES WITH THE MEDIUM-TERM PALEOCLIMATE RECORD

Separating the effects of short-term human-induced climate changes from natural variations on longer-term timescales can be difficult. Present-day global warming is unusual for the climate record of the past 1,300 years, but it has counterparts induced by natural causes about 125,000 years ago and in the older geological record. The last time (125,000 years ago) climates warmed as significantly as the planet is now experiencing, loss of polar ice led to sea-level rise of 13–20 feet (4–6 m), suggesting that the world's coastlines are in grave danger of moving inland to higher ground. Ice core data show that temperatures in Greenland were 4–7°F (3–5°C) hotter than at present, a level that many models predict will be reached by the end of this century. The last 50 years appear to be the hottest in the past 1,300 years, but significant fluctuations have occurred.

The measured increases in anthropogenic greenhouse gases can more than account for the measured temperature rise of the surface of the Earth in the past 50–100 years. The less-than-expected warming is probably related to lowering of the temperature by aerosols from volcanic eruptions and dust from desert environments. These measurements strongly suggest that present-day global warming is being forced by the human-induced injection of greenhouse gases to the atmosphere, not to other long-term climate-forcing mechanisms that have controlled other global warming and cooling events in past geological times.

The measured surface warming is nearly global in scale, with Antarctica the exception; it is sheltered from parts of the global atmosphere/ocean system. Climate models are consistent with the global warming produced by anthropogenic causes. Many local variations exist, such as "warming holes," where local atmospheric effects are stronger than the global changes.

Global warming is also likely affecting wind patterns, the most extreme hot and cold nights, extratropical storm patterns, and an increase in heat waves. Effects are stronger in the Northern than in the Southern Hemisphere.

SEA-LEVEL CHANGES

Global sea levels are currently rising as a result of the melting of the Greenland and Antarctica ice sheets and thermal expansion of the world's ocean waters due to global warming. The Earth is presently in an interglacial stage of an ice age, and sea levels have risen nearly 400 feet (130 m) since the last glacial maximum 20,000 years ago, and about six inches (15.25 cm) in the past 100 years. The rate of sea-level rise seems to be accelerating and may presently be as much as an inch (2.5 cm) every 8–10 years. If all the ice on both ice sheets were to melt, global sea levels would rise by 230 feet (70 m), inundating most of the world's major cities and submerging large parts of the continents under shallow seas. The coastal regions of the world are densely populated and are experiencing rapid population growth. Approximately 100 million people presently live within 3 feet (1 m) of the present day sea level. If sea level were to rise rapidly and significantly, the world would experience an economic and social disaster on a magnitude not yet experienced by the civilized world. Many areas would become permanently (on human timescales) flooded or subject to inundation by storms, beach erosion would be accelerated, and water tables would rise.

The Greenland and Antarctic ice sheets have significant differences that cause them to respond differently to changes in air and water temperatures. The Antarctic ice sheet is about 10 times as large as the Greenland ice sheet, and since it sits on the South Pole, Antarctica dominates its own climate. The surrounding ocean is cold even during summer, and much of Antarctica is a cold desert with low precipitation rates and high evaporation potential. Most meltwater in Antarctica seeps into underlying snow and simply refreezes, with little running off into the sea. Antarctica hosts several large ice shelves fed by glaciers moving at rates of up to a thousand feet (300 m) per year. Most ice loss in Antarctica is accomplished through calving and basal melting of the ice shelves, at rates of about 10–15 inches (25–38 cm) per year.

In contrast, Greenland's climate is influenced by warm North Atlantic currents and its proximity to other land masses. Climate data measured from ice cores taken from the top of the Greenland ice cap show that temperatures have varied significantly in cycles of years to decades. Greenland also experiences significant summer melting and abundant snowfall, and has few ice shelves; its glaciers move quickly at rates of up to miles (several km) per year. These fast-moving glaciers can drain a large amount of ice from Greenland in relatively short periods of time.

The Greenland ice sheet is thinning rapidly along its edges, loosing an average of 15–20 feet (4.5–6 m) in the past decade. In addition tidewater glaciers and the small ice shelves in Greenland are melting on an order of magnitude faster than the Antarctic ice sheets, with rates of melting between 25–65 (7.6–20 m) feet per year. About half of the ice lost from Greenland is through surface melting that runs off into the sea. The other half of ice loss is through calving of outlet glaciers and melting along the tidewater glaciers and ice shelf bases. If just the Greenland ice sheet melts, the water released will contribute another 23 feet (7 m) to sea-level rise, to a level not seen since 125,000 years ago.

These differences between the Greenland and Antarctic ice sheets lead them to play different roles in global sea-level rise. Greenland contributes more to the rapid, short-term fluctuations in sea level, responding to short-term changes in climate. In contrast, most of the world's water available for raising sea level is locked up in the slowly changing Antarctic ice sheet. Antarctica contributes more to the gradual, long-term, sea-level rise.

Data released by the IPCC in 2007 suggest that the current melting of glaciers is largely the result of the recent warming of the planet in the past 100 years through greenhouse warming. Greenhouse gases have been increasing at a rate of more than 0.2 percent per year, and global temperatures are rising accordingly. The most significant contributor to the greenhouse gas buildup is CO_2, produced mainly by burning fossil fuels. Other gases that contribute to greenhouse warming include carbon monoxide, nitrogen oxides, methane (CH_4), ozone (O_3), and chlorofluorocarbons. Methane is produced by gas from grazing animals and termites, whereas nitrogen oxides are increasing because of the increased use of fertilizers and automobiles, and chlorofluorocarbons are increasing as a result of release from aerosols and refrigerants. Together the greenhouse gases have allowed short-wavelength incoming solar radiation to penetrate the gas in the upper atmosphere but trapped the solar radiation after it is reemitted from the Earth in a longer wavelength. The trapped radiation causes the atmosphere to heat up, leading to greenhouse warming. Other factors also influence greenhouse warming and cooling, including the abundance of volcanic ash in the atmosphere and solar luminosity variations, as evidenced by sunspot variations.

Measuring global (also called eustatic) sea-level rise and fall is difficult because many factors influence the relative height of the sea along any coastline. Vertical motions of continents, called epeirogenic movements, may be related to plate tectonics; they rebound from being buried by glaciers or to changes in the amount of heat added to the base of the continent by mantle convection. Continents may rise or sink vertically, causing apparent sea-level change, but these sea-level changes are relatively slow compared with changes induced by global warming and glacial melting. Slow, long-term, sea-level changes can also be induced by changes in the amount of seafloor volcanism associated with seafloor spreading. At some times in Earth history seafloor spreading was particularly vigorous, and the increased volume of volcanoes and the midocean ridge system caused global sea levels to rise.

Steady winds and currents can mass water against a particular coastline, causing a local and temporary sea-level rise. Such a phenomena is associated with the El-Nino-Southern Oscillation (ENSO), causing sea levels to rise by 4–8 (10–20 cm) inches in the Australia-Asia region. When the warm water moves east in an ENSO event, sea levels may rise 4–20 inches (10–50 cm) across much of the North and South American coastlines. Other atmospheric phenomena can also change sea level by centimeters to meters locally, on short timescales. Changes in atmospheric pressure, salinity of sea waters, coastal upwelling, onshore winds, and storm surges all cause short-term fluctuations along segments of coastline. Global or local warming of waters can cause them to expand slightly, causing a local sea-level rise. The extraction and use of groundwater and its subsequent release into the sea is likely causing an additional sea-level rise of about 0.05 inches (0.13 cm) per year. Seasonal changes in river discharge can temporarily change sea levels along some coastlines, especially where winter cooling locks up large amounts of snow that melt in spring.

Attempts to estimate eustatic sea-level changes must be able to average out the numerous local and tectonic effects to arrive at a globally meaningful estimate of sea-level change. Most coastlines seem to be dominated by local fluctuations that are larger in magnitude than any global sea-level rise. Recently satellite radar technology has precisely measured sea surface height and documented annual changes in sea level. Radar altimetry can map sea surface elevations to the sub-inch scale, and to do this globally, providing an unprecedented level of understanding of sea surface topography. Satellite techniques support the concept that global sea levels are rising at about 0.1 inches (.25 cm) per decade.

See also ATMOSPHERE; CLIMATE, CLIMATE CHANGE; DESERTS; GLACIER, GLACIAL SYSTEMS.

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Goldschmidt, Victor M. (1888–1942) Swiss *Chemist, Geochemist, Mineralogist* Victor Goldschmidt studied chemistry, mineralogy, and geology at the University of Kristiania in Norway and is often considered to be the father of modern geochemistry. His work was greatly influenced by the Norwegian petrologist and mineralogist W. C. Bogger and also by earth scientists Paul von Groth and Friedrich Becke. Goldschmidt received a doctorate in geology in 1911 with his thesis "The Contact Metamorphism in the Kristiania Region." He became a full professor of geochemistry and director of the mineralogical institute of the University of Kristiania (later Oslo) in 1914. His doctoral thesis concerned the factors governing the mineral associations in contact-metamorphic rocks and was based on the samples he had collected in southern Norway. In later years he became a professor on the faculty of natural sciences at Göttingen and head of its mineral institute. While at Kristiania he began geochemical investigations on the noble gases and alkali metals, and the siderophilic and lithophilic elements. He produced a model of the Earth that showed how these different elements and metals accumulated in various geological domains based on their charge and size, and on the polarizability of their ions. Goldschmidt is one of the pioneers in geochemistry who explained the composition of the environment.

EARLY LIFE, CAREER, AND SCIENTIFIC CONTRIBUTIONS

Victor Moritz Goldschmidt was born in Zurich, Switzerland, on January 27, 1888, to Heinrich J. Goldschmidt and Amelie Koehne. In 1901 Victor's father accepted a position as professor of chemistry in Kristiania (Oslo), and the family moved from Switzerland to Norway. Victor studied geology and mineralogy in Norway, completing a doctorate at age 23 in 1911, consisting of two papers, "Die Kontaktmetamorphose im Kristianiagebiet" (Contact metamorphism in the Kristiana region) and "Geologisch-petrographische Studien im Hochgebirge des südlichen Norwegens" (Geologic and petrographic studies in the Hochgebirge area, southern Norway). In 1912 he was awarded Norway's most distinguished scientific award, the Fridtjof Nansen medal, for his Ph.D. research. At the same time he was made an associate professor (docent) of mineralogy and petrography at the University of Oslo. After completing his Ph.D. Goldschmidt authored a series of papers widely considered to represent the beginning of modern geochemistry and was highly influential in the fields of mineralogy, geology, crystallography, and theoretical chemistry. Some of his most important work included descriptions of the role of ionic radii in determining the geochemical behavior of the elements. He stayed in Norway at the University of Kristiania as a professor of mineralogy, then moved back to Oslo in 1935.

In 1942 while Norway was under German occupation, Europe was in a state of chaos from the Nazi occupation, and Goldschmidt was arrested on October 26, 1942, for being a Jew. He was sent to the Berg concentration camp near Tonsberg, Norway, and was almost deported to Auschwitz, but he was held in Norway on the condition that he lend his scientific expertise to help the German war effort. He fled to Sweden as soon as he could, then to England, and returned to Oslo after the war in 1945, but died at the age of 59, on March 20, 1947.

See also GEOCHEMISTRY; MINERAL, MINERALOGY.

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Gondwana, Gondwanaland

Gondwana is the Late Proterozoic–Late Paleozoic supercontinent of the Southern Hemisphere, named by British/Austrian geologist Eduard Suess after the Gondwana System of southern India. The name Gondwana means "land of the Gonds" (an ancient tribe in southern India), so the more common rendition of the name Gondwanaland for the southern supercontinent is technically improper, meaning "land of the land of the Gonds." The supercontinent includes the present continents and continental fragments of Africa, South America, Australia, Arabia, India, Antarctica, and many smaller fragments. Most of these continental masses amalgamated in the latest Precambrian during closure of the Mozambique Ocean and several other oceans, seas, and basins. It persisted as a supercontinent until they joined with the northern continents in the Carboniferous to form the supercontinent Pangaea.

Geologists have matched the different fragments of Gondwana with others using alignment between belts of similar-aged deformation, metamorphism, and mineralization, as well as common faunal, floral, and paleoclimatic belts. The formation and breakup of Gondwana is associated with one of the most remarkable explosions of new life-forms in the history of the planet, the change from simple, single-celled organisms and soft-bodied fauna to complex, multicelled organisms. The formation and dispersal of supercontinents strongly influences global climate and the availability of different environmental niches for biological development, linking plate tectonic and biological processes.

Since the early 1990s a consensus has emerged that Gondwana formed near the end of the Neoproterozoic from the fragmented pieces of an older supercontinent, Rodinia, itself assembled near the end of the Grenville cycle (~1,100 Ma). The now standard model of Gondwana's assembly begins with the separation of East Gondwana (Australia, Antarctica, India, and Madagascar) from the western margin of Laurentia, and the fanlike aggregation of East and West Gondwana. The proposed assembly closed several ocean basins, including the very large

Glossopteris leaf fossil from Permian period found in Coohah, New South Wales, Australia. *Glossopteris* is one of the diagnostic flora used by Alfred Wegener and others to match paleoclimate and paleobiological zones across the southern continents, to re-create the former positions of these continents in the proposed supercontinent of Gondwana. *(Martin Land/Photo Researchers, Inc.)*

Mozambique Ocean, and turned the constituents of Rodinia inside-out, such that the external or "passive" margins in Madagascar and elsewhere became collisional margins in latest Precambrian and earliest Cambrian time.

The notion of a single, short-lived collision between East and West Gondwana is an oversimplification, since geologic relations suggest that at least three major ocean basins closed during the assembly of Gondwana (Pharusian, Mozambique, Adamastor), and published geochronology demonstrates that assembly was a protracted affair. Current research aims to understand these relationships. For example, an alternative two-stage model for closure of the Mozambique Ocean has been recently advanced that ascribes an older "East African" Orogeny (~680 Ma) to collision between Greater India (i.e., India-Tibet-Seychelles-Madagascar-Enderby Land) and the conjoined Congo and Kalahari cratons. A younger "Kuunga" event (~550 Ma) that represents the collision of Australia–East Antarctica with proto-Gondwana followed, thus completing Gondwana's assembly near the end of the Neoproterozoic.

An international research journal *Gondwana Research* was launched in the 1990s in which scientists working on a variety of issues about the landmasses of Gondwana have published their research results. This journal has become a widely used forum in which to present and discuss new data related to the former supercontinent, as well as its geology, lifeforms, mineral deposits, and past climates.

See also PROTEROZOIC; SUPERCONTINENT CYCLES.

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Grabau, Amadeus William (1870–1946) German-American *Geologist, Paleontologist*

Amadeus William Grabau was born on January 9, 1870, in Cedarburgh, Wisconsin. He was a great contributor to systematic paleontology and stratigraphic geology and also a respected professor and writer. He spent half of his professional life in the United States and the last 25 years in China. Grabau studied at the Massachusetts Institute of Technology (MIT) and received a master of science and a doctorate of science degree at Harvard University, then returned as faculty at MIT from 1892 to 1897. He moved to Rensselaer Polytechnic Institute in Troy, New York, from 1899 to 1901, and became a professor in paleontology at Columbia University in New York City in 1901. In 1912 Grabau married Mary Antin, a Russian immigrant from a shtetl who wrote a best-selling autobiography, *The Promised Land.* In World War I Grabau defended Germany's actions, which led to his divorce from Mary and his being fired from Columbia University. In 1919 Grabau moved to China and became a professor at Peking National University (now called Peking University).

In the first 20 years of his career he was one of the country's leading scientists in paleontology, stratigraphy, and sedimentary petrology. The greatest effect of his scientific work has been his contributions to the principles of paleoecology and to the genetic aspects of sedimentary paleontology. Paleoecology uses fossil data to reconstruct information about past ecosystems. Grabau was interested in relating the ecosystems to differences in the organism that made the fossils he was studying. His stratigraphic work was also influential; not only did it bring about a more developed understanding of the subject, but it was the source of understanding Earth movements. The concepts involved in his polar control theory, pulsation theory, and the separation of Pangaea allowed for the imaginative syntheses of geologic evidence. After Grabau moved to China, he conducted a geologic survey of much of the country, and from this work he became known as the father of Chinese geology. Grabau died on March 20, 1956, in what is now called Beijing.

Grabau published more than 10 books during his career, including *North American Index Fossils* (1909, 1910), *Principles of Stratigraphy* (1913), *Textbook of Geology,* 2 vols. (1920–21), *Silurian Fossils of Yunnan* (1920), *Ordovician Fossils of North China* (1921), *Paleozoic Corals of China* (1921), *Stratigraphy of China* (1924–25), *Migration of Geosynclines* (1924), *Early Permian Fossils of China* (1934), and *Rhythm of the Ages* (1940). This influential geologist and paleontologist received numerous awards and was a member of the following institutes: the Geological Society of America, New York Academy of Science, and Geological Society of China. He was also an honorary member of the Peking Society of

Natural History, the China Institute of Mining and Metallurgy, the Academia Sinica, and the Academia Peipinensis.

See also ASIAN GEOLOGY; HISTORICAL GEOLOGY; PALEONTOLOGY; SEDIMENTARY ROCK, SEDIMENTATION.

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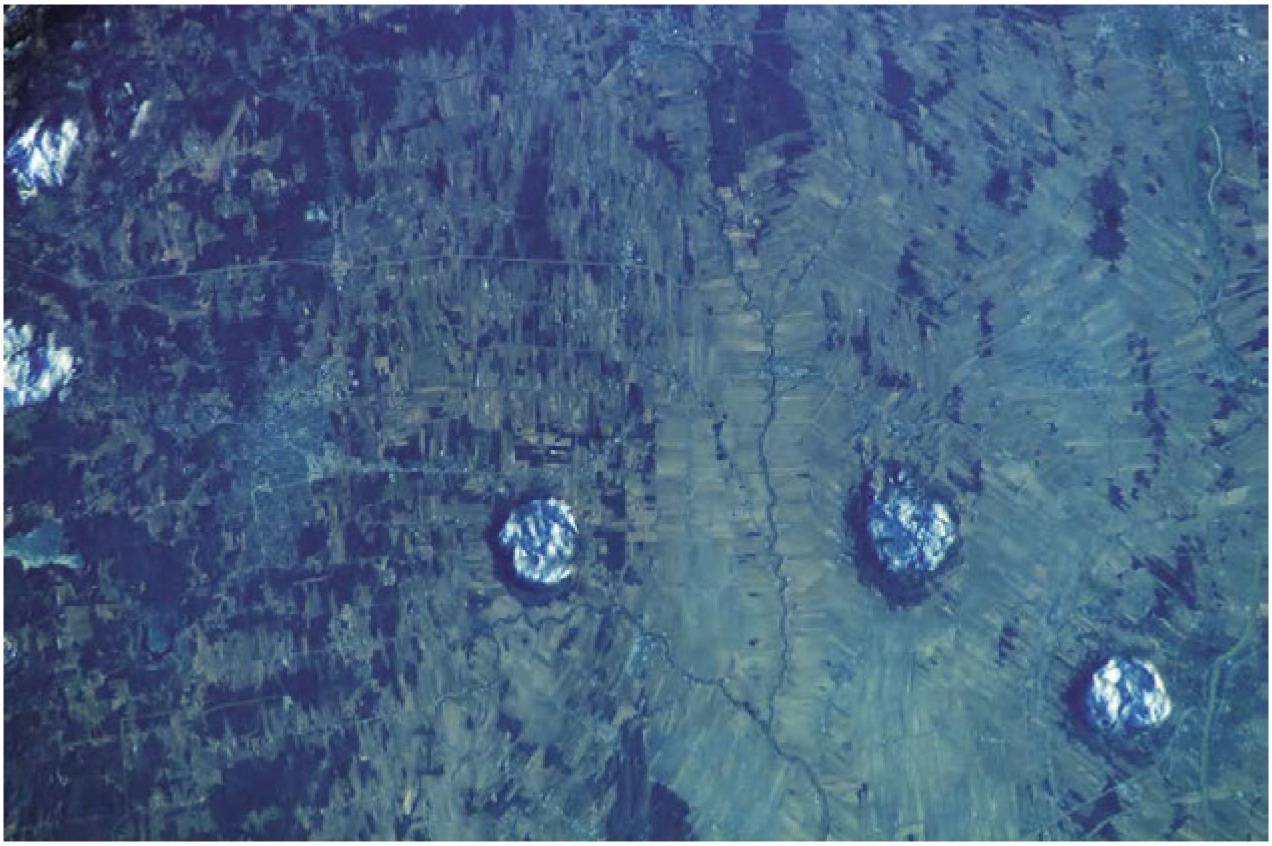
granite, granite batholith A coarse-grained igneous plutonic rock with visible quartz, potassium, and plagioclase feldspar, and dark minerals such as biotite or amphibole is generally known as granite, but the International Union of Geological Scientists (IUGS) define granite more exactly as a plutonic rock with 10–50 percent quartz and the ratio of alkali to total feldspar in the range of 65–90 percent.

Granites and related rocks are abundant in the continental crust and may be generated either by melting preexisting rocks or, in lesser quantities, by differentiation via fractional crystallization of basaltic magma. Many granites are associated with convergent-margin or Andean-style magmatic arcs, and include such large plutons and batholiths as those of the Sierra Nevada batholith, Coast Range batholith, and many others along the American Cordillera. Granites are also a major component of Archean cratons and granite greenstone terranes.

Many building stones are granitic, since they tend to be strong, durable, and nonporous and exhibit many color and textural varieties. Granite often forms rounded hills with large round or oblong boulders scattered over the hillside. Many of these forms are related to weathering along several typically perpendicular joint sets, where water infiltrates and reacts with the rock along the joint planes. Three sets of perpendicular joints define cubes in three dimensions; large blocks get weathered out and eventually rounded as the corners weather faster than the other parts of the joint surface, since they have more surface exposed to weathering agents. Granite also commonly forms exfoliation domes, in which large sheets of rock weather off and slide down mountain sides and inselbergs, isolated steep-sided hills that

Mount Whitney and Alabama Hills outside Lone Pine, California. These mountains form part of the Sierra Nevada granite batholith. *(Mike Norton, Shutterstock, Inc.)*



Plutons in Monteregian Hills, Quebec, Canada, taken by Expedition 14 crew member in the *International Space Station,* April 18, 2007 *(Earth Sciences and Image Analysis Laboratory, NASA Johnson Space Center)*

remain on a more weathered plain. Many granites weather ultimately to flat or gently rolling plains covered by erosional detritus including cobbles, boulders, and granitic gravels.

Pluton is a general name for a large, cooled, igneous intrusive body in the Earth. Some plutons are so large that they have special names—batholiths are plutons with a surface area greater than 60 square miles (100 km^2). Several types of igneous intrusions are produced by magmas (generated from melting rocks in the Earth) and intrude the crust, taking one of several forms. The specific type of pluton is based on its geometry, size, and relations to the older rocks surrounding the pluton, known as country rock. Concordant plutons have boundaries parallel to layering in the country rock, whereas discordant plutons have boundaries that cut across layering in the country rock. Dikes are tabular but discordant intrusions, and sills are tabular and concordant intrusives. Volcanic necks are conduits connecting a volcano with its underlying magma chamber. A famous example of a volcanic neck is Devils Tower, Wyoming.

Batholiths and plutons have different characteristics and relationships to surrounding country rocks based on the depth at which they intruded and crystallized. Epizonal plutons are shallow and typically have crosscutting relationships with surrounding rocks and tectonic foliations. They may have a metamorphic aureole surrounding them, where the country rocks have been heated by the intrusion and grew new metamorphic minerals in response to the heat and fluids escaping from the batholith. Rings of hard-contact metamorphic rocks in the metamorphic aureole surrounding batholiths are known as hornfels rocks. Mesozonal rocks intrude the country rocks at slightly deeper levels than the epizonal plutons but not as deep as catazonal plutons and batholiths. Catazonal plutons and batholiths tend to have contacts parallel with layering and tectonic foliations in the surrounding country rocks and do not show such a large temperature gradient with the country rocks as those from shallower crustal levels. This is because all the rocks are at relatively high temperatures. Catazonal plutons tend to be foliated, especially around their margins and contacts with the country rocks.

Batholiths are derived from deep crustal or deeper melting processes and may be linked to surface volcanic rocks. Batholiths form large parts of the continental crust and are associated with some metallic mineral deposits; they are used for building stones.

PLUTON EMPLACEMENT MECHANISMS

The volume of magma that intruded the Earth's crust in some plutons and batholiths is enormous. All the magma in these plutons had to create space in the crust for it to intrude into, since the plutons typically intrude into preexisting continents.

Geologists have long speculated on how such large volumes of magma intrude the crust, and what relationships these magmas have on the style of volcanic eruption. One mechanism that may operate is assimilation, where the magma melts surrounding rocks as it rises, causing them to become part of the magma. In doing so the magma becomes cooler, and its composition changes to reflect the added melted country rock. Assimilation causes magmas to rise only a limited distance. High pressure can force some magmas into the crust. One variation of this forceful emplacement style is diapirism, whereby the weight of surrounding rocks pushes down on the melt layer, which squeezes up through cracks that can expand and extend, forming volcanic vents at the surface. Stoping is a mechanism whereby big blocks are thermally shattered and drop off the top of the magma chamber, falling into it, much like a glass ceiling breaking and falling into the space below. Many if not most plutons seem to be emplaced into structures such as faults, utilizing the weakness provided by the structure for the emplacement of the magma. Some plutons are emplaced into active faults, intruding into spaces created by gaps that open between misaligned segments of the moving fault zone.

See also CRATON; GRANITE, GRANITE BATHOLITH; IGNEOUS ROCKS; PETROLOGY AND PETROGRAPHY; STRUCTURAL GEOLOGY; WEATHERING.

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gravity, gravity anomaly Gravity is the attraction between any body in the universe and all other bodies described by the inverse square law

$$F = (M_1M_2)/r^2$$

where F represents the force of gravity, M represents the masses of the two bodies that are attracted, and r represents the distance between the objects. Often the term *gravity* refers specifically to the force exerted on any body on or near the surface of the Earth by the mass of the Earth and any centrifugal force resulting from the planet's rotation. A gravity anomaly is the difference between the observed value of gravity at a point and the theoretically calculated value of gravity at that point, based on a simple gravity model. The value of gravity at a point reflects the distribution of mass and rock units at depth, as well as topography. The average gravitational attraction on the surface is 32 feet per second squared (9.8 m/s^2), with one gravity unit (g.u.) being equivalent to one ten-millionth of this value. Another, older unit of measure, the milligal, is equivalent to 10 g.u. The range in gravity on the Earth's surface at sea level is about 50,000 g.u., or from 32.09–32.15 feet per second squared (9.78–9.83 m/s^2). A person would weigh slightly more at the equator than at the poles because the Earth has a slightly larger radius at the equator than at the poles.

Geologically significant variations in gravity are typically only a few tenths of a gravity unit, so instruments to measure gravity anomalies must be very sensitive. Some gravity surveys are made with a series of gravity meters on the surface, whereas others employ observations of the perturbations of satellite orbits.

The determination of gravity anomalies involves subtracting the effects of the overall gravity field of the Earth, accomplished by removing the gravity field at sea level (geoid), leaving an elevation-dependent gravity measurement. This measurement reflects a lower gravitational attraction with height and distance from the center of the Earth, as well as an increase in gravity caused by the gravitational pull of the material between the point and sea level. The free-air gravity anomaly is a correction of the measured gravity calculated by using only the elevation of the point and the radius and mass of the Earth. A second correction, which depends on the shape and density of rock masses at depth, is the Bouguer gravity anomaly. Sometimes a third correction is applied to gravity measurements, known as the isostatic correction. This applies when a load such as a mountain, sedimentary basin, or other mass is supported by mass deficiencies at depth, much like an iceberg floating lower in the water. There are several different mechanisms of possible isostatic compensation, however, and it is often difficult to know which mechanisms are important on different scales. Therefore this correction is often not applied.

Different geological bodies are typically associated with different magnitudes and types of gravity anomalies. Belts of oceanic crust thrust on continents (ophiolites) represent unusually dense material and are associated with positive gravity anomalies of up to several thousand g.u. Likewise, unusually dense massive sulfide metallic ore bodies are also associated with positive gravity anomalies. Salt domes, oceanic trenches, and mountain ranges all represent an increase in the amount of low-density material in the crustal column and are therefore associated with increasingly negative gravity anomalies, with negative values of up to 6,000 g.u. associated with the highest mountains on Earth, the Himalayan chain.

See also GEOID; GEOPHYSICS.

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gravity wave The term *gravity wave* can be used in two different contexts. The first is in fluid dynamics in reference to waves generated in a fluid medium or at the interface between two fluids, such as air and water. The second context is in astrophysics and general relativity theory.

In fluid dynamics gravity waves form when a unit of fluid at an interface between two different fluids moves to a region with a different density. When this happens gravity attempts to restore the unit of fluid to equilibrium, forming an oscillating wave. Ocean waves generated by the wind are examples of one type of gravity wave known as surface gravity waves. When gravity waves form at boundaries between fluids in the ocean or atmosphere, they are known as internal gravity waves.

The transfer of energy from wind to the ocean surface causes the formation of surface gravity waves on the sea surface by two different mechanisms. If the surface of the ocean is initially flat and a turbulent wind blows across this surface, the fluctuation in the wind imposes fluctuating stresses on the ocean surface, oriented parallel and perpendicular to the surface. These stresses act as a forcing mechanism that may find a matching frequency and wave number for a mode of vibration of the sea surface, then the surface will begin to vibrate as a gravity wave. As more energy is added by the wind, a resonance grows, and the waves grow in amplitude. A resonance is the tendency of a system to oscillate at a maximum amplitude at specific frequencies, known as the resonance frequencies for that system. Once the sea-air surface has this initial roughness, a second process helps the waves grow. In this phase the waves interact with the turbulent flow of the overlying air, with energy transferred to the new waves in a critical boundary layer that forms at a specific height where the wave speed equals the mean turbulent flow. This mechanism continues until the wind stops, or the distance (fetch) it can act on ends (where land is encountered), and the waves continue to grow until either of those points is met.

Gravity waves in the atmosphere transfer momentum from the troposphere (lower 6–7 miles [9.7–11 km] of the atmosphere) to the mesosphere (31–53 [50–85 km] miles above the surface], and often form in response to the movement of frontal systems and to the passage of air over mountain peaks. Low-altitude gravity waves may resemble undulating clouds and do not significantly change the velocity of the moving air mass. Gravity waves at higher altitudes at the boundary with low-density air become higher in amplitude and break, however, transferring significant energy and momentum to the mean flow of air in the mesosphere. They are thus extremely important in controlling the dynamics of the middle atmosphere.

Gravity waves are also prominent in Albert Einstein's theory of relativity, which forms the foundation of modern ideas about gravity. In this usage gravity waves can be thought of as gravitational radiation that results from a change in the strength of a gravitational field. In relativity theory any mass that accelerates through space will produce a small distortion in the space through which it is traveling, causing a change in the gravitational field, or a gravity wave, that should be emitted at the speed of light. However, the gravitational force is so small compared with the electromagnetic force that the distortions produced by gravity waves are expected to be less that the diameter of an atomic nucleus for masses the size of galaxies, and no one has yet detected a gravity wave in this relativistic sense. But, active research programs are attempting to detect gravity waves from interactions of massive objects such as merging binary star systems, black holes swallowing stars, and other galactic collisions. In one example scientists have observed the collapse of a binary star system to produce a shrinking orbit with energy loss from the system consistent with energy being carried away from the system by gravity waves as predicted by Einstein's relativity theory, but the waves themselves have not been detected.

See also ATMOSPHERE; EINSTEIN, ALBERT; GRAVITY, GRAVITY ANOMALY.

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greenhouse effect The greenhouse effect is commonly used to explain a phenomenon characterized by abnormal warmth on Earth in response to the atmosphere trapping incoming solar radiation. Global climate is a balance between the amount of solar radiation received and the amount of this energy retained in a given area. The planet receives about 2.4 times as much heat in the equatorial regions as in the polar regions. The atmosphere and oceans respond to this unequal heating by setting up currents and circulation systems that redistribute the heat more evenly. These circulation patterns are, in turn, affected by the ever-changing pattern of the distribution of continents, oceans, and mountain ranges.

The amounts and types of gases in the atmosphere can modify the amount of incoming solar radiation. For instance, cloud cover can cause much of the incoming solar radiation to reflect back to space before it reaches the lower atmosphere. On the other hand, certain types of gases (known as greenhouse gases) allow incoming short-wavelength solar radiation to enter the atmosphere but trap this radiation when it tries to escape in its longer-wavelength reflected form. This causes a buildup of heat in the atmosphere and can lead to a global warming known as the greenhouse effect.

The amount of heat trapped in the atmosphere by greenhouse gases has varied greatly over Earth's history. One of the most important greenhouse gases is carbon dioxide (CO_2) that plants (which release oxygen, O_2, to the atmosphere) now take up by photosynthesis. In the early part of Earth history (the Precambrian), before plants covered the land surface, photosynthesis did not remove CO_2 from the atmosphere, so CO_2 levels were much higher than at present. Marine organisms also take up atmospheric CO_2 by removing it from the ocean surface water (which is in equilibrium with the atmosphere) to use in combination with calcium to form their shells and mineralized tissue. These organisms make $CaCO_3$ (calcite), the main component of limestone, a rock composed largely of the remains of dead marine organisms. Approximately 99 percent of the planet's CO_2 is presently removed from the atmosphere/ocean system, because it has been locked in rock deposits of limestone on the continents and on the seafloor. If this amount of CO_2 were released back into the atmosphere, global temperature would increase dramatically. In the early Precambrian, when this CO_2 was free in the atmosphere, global temperatures averaged about 550°F (290°C).

The atmosphere redistributes heat quickly by forming and redistributing clouds and uncondensed water vapor around the planet along atmospheric circulation cells. Oceans are able to hold and redistribute more heat because of the greater amount of water they contain, but they redistribute this heat more slowly than the atmosphere. Surface currents are formed in response to wind patterns, but deep ocean currents (which move more of the planet's heat) follow courses that are more related to the bathymetry (topography of the seafloor) and the spinning of Earth than they are related to surface winds.

The balance of incoming and outgoing heat from Earth has determined the overall temperature of the planet through time. Examination of the geological record has enabled paleoclimatologists to reconstruct periods when Earth had glacial periods, hot and dry periods, hot and wet periods, or cold and dry periods. In most cases Earth has responded to these changes by expanding and contracting its climate belts. Warm periods see an expansion of the warm subtropical belts to high latitudes, and cold periods see an expansion of the cold climates of the poles to low latitudes.

HISTORICAL DEVELOPMENT OF THE GREENHOUSE EFFECT CONCEPT

The historical development of the greenhouse effect theory stems from a concept first coined by the French physicist Edme Mariotte (1620–84) in 1681, who noted that light and heat from the Sun easily passes through a sheet of glass, but that heat from candles and other sources does not. This concept was then extended by the French mathematician Joseph Fourier (1768–1830) in 1824 to the atmosphere by noting that heat and light from the Sun can pass from space through the atmosphere, but heat radiated back to the atmosphere from Earth may get trapped by some of the atmospheric gases, just as heat from a candle is partly blocked by a glass pane. Then in 1861 the Irish physicist John Tyndall (1820–1893) discovered that the complex molecules of water (H_2O) and carbon dioxide (CO_2) were mainly responsible for the absorption of heat radiated back from Earth, and that other atmospheric gases such as nitrogen and oxygen did not play a role in this effect. Tyndall noted that simple changes in the concentrations of CO_2 and H_2O could alternately cool and heat the atmosphere, producing "all the mutations of climate which the researches of geologists reveal." The next step in understanding the greenhouse effect came from the work of Swedish physicist and chemist Svante Arrhenius (1859–1927) in 1896, who calculated that a 40 percent increase or decrease in the atmospheric concentration of CO_2 could trigger the advance or retreat of continental glaciers, setting off the glacial and interglacial ages. Much later a change in the atmospheric CO_2 of this magnitude was documented in cores of the Greenland ice sheet, as predicted by Arrhenius.

Carbon dioxide can vary naturally in the atmosphere through a variety of driving mechanisms, including changes in volcanism, erosion and plate tectonics, and ocean-atmosphere interactions. The modern concept of linking greenhouse gases with the burning of fossil fuels by humans was formulated by steam engineer and amateur meteorologist Guy Stewart Callendar (1898–1964) in 1938, who calculated that a doubling of atmospheric CO_2 by burning fossil fuels would result in an average global temperature increase of about 3°F (2°C), with more heating at the poles. Callendar made prescient predictions that humans are changing the composition of the atmosphere at a rate that is "exceptional" on geological timescales, and he sought to understand what effects these changes might have on climate. His prediction was that the "principal result of increasing carbon dioxide will be a gradual increase in the mean temperature of the colder regions of the Earth." These predictions were first confirmed in 1947 when the Swedish climatologist Hans Wilhelmsson Ahlmann (1889–1974) reported a 1–2° F (1.3°C) increase in the average temperature of the North Atlantic sector of the Arctic. At this time the nature of the complex interactions of the carbon cycle and exchange of CO_2 in the atmosphere-ocean system was not well understood, however, and many scientists attributed the entire temperature rise to human production of greenhouse gases. Later studies of ocean-atmosphere relationships, and biogeochemistry, showed more complex relationships. Later, in the 1970s, effects of aerosols in the atmosphere, principally to reflect solar radiation to space and cooling Earth, began to be appreciated as another component of the greenhouse effect. The current state of knowledge of the complex physical, chemical, biological, and other processes associated with the greenhouse effect are described in the *Climate Change 2007* report issued by the Intergovernmental Panel on Climate Change.

See also ATMOSPHERE; CLIMATE; CLIMATE CHANGE; GLOBAL WARMING.

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greenstone belt

A greenstone belt is an elongate accumulation of generally mafic volcanic and plutonic rocks, typically associated with assemblages of sedimentary rocks that include sandstones, mudstones, banded iron formations, and, less commonly, carbonates and mature sedimentary rocks. Most greenstone belts are Archean or at least Precambrian in age, although similar sequences are known from orogenic belts of all ages. Nearly all are metamorphosed to greenschist through amphibolite facies and intruded by a variety of granitoid rocks. Older gneissic rocks are associated with some greenstone belts, although most of these are in fault contact with the greenstone belts.

Greenstone belts display a wide variety of shapes and sizes and are distributed asymmetrically across Archean cratons in a manner reminiscent of tectonic zonations in Phanerozoic orogens. For instance, the Yilgarn craton in Australia has mostly granitic gneisses in the southwest, mostly 2.9 billion-year-old greenstones throughout the central craton, and 2.7 billion-year-old greenstones in the east. The Slave Province in Canada contains remnants of a circa 4.2–2.9 billion-year-old gneissic terrain in the western part of the province, dominantly mafic greenstone belts in the center, and 2.68 billion-year-old mixed mafic, and intermediate and felsic calc-alkaline volcanic rocks in the eastern part of the province. Other cratons are also asymmetric in this respect; for example, the Zimbabwe craton, in Africa, has mostly granitic rocks in the east and more greenstones in the west. The Superior Province contains numerous subparallel belts, up to thousands of miles long, that are distinct from each other but similar in scale and rock type to Phanerozoic orogens. These distributions of rock types are analogous to asymmetric tectonic zonations, which are products of plate tectonics in younger orogenic belts, and emphasize that greenstone belts are perhaps only parts of once larger orogenic systems.

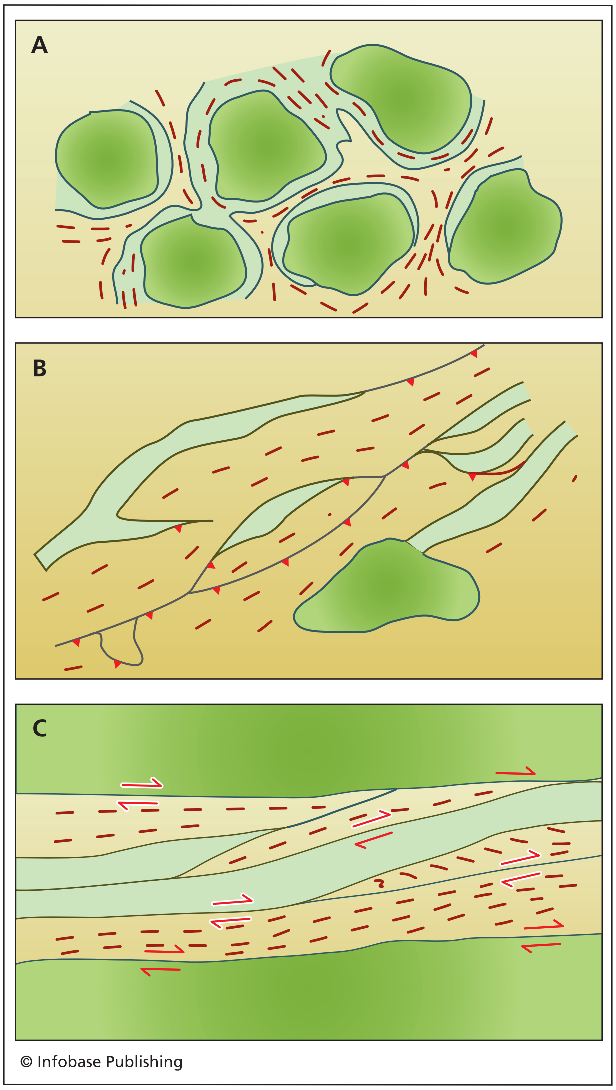
There are three significantly different end-member regional outcrop patterns of greenstone belts reflecting the distribution of these belts within cratons. These include broad domal granitoids with interdomal greenstones; broad greenstone terrains with internally branching lithological domains and irregular granitoid contacts; and long, narrow, and straight greenstone belts. The first pattern includes mostly granitoid domes with synformal greenstone belts, which result from either interference folding or dome-shaped granitoids. The second pattern includes many of the terranes with thrust belt patterns, including much of the Yilgarn Province in western Australia and the Slave Province of Canada. Contacts with granitoids are typically intrusive. The third pattern includes composite thrust/strike slip belts dominated by late strike-slip shear zones along one or more sides of the belt. Granite-greenstone contacts are typically a fault or shear zone.

Until recently few complete ophiolite-like sequences were recognized in Archean greenstone belts, leading some workers to the conclusion that no Archean ophiolites or oceanic crustal fragments are preserved. Research documenting partial dismembered ophiolites in several greenstone belts and a complete ophiolite sequence in the North China craton recently challenged these ideas. Archean oceanic crust was possibly thicker than Proterozoic and Phanerozoic counterparts, and this resulted in accretion predominantly of the upper basaltic section of oceanic crust. The crustal thickness of Archean oceanic crust may have resembled modern oceanic plateaus. If this were the case, complete Phanerozoic-like ophiolite sequences would have been very unlikely to be preserved from Archean orogenies. In contrast, only the upper, pillow lava–dominated sections would likely be accreted. Archean greenstone belts have an abundance of accreted ophiolitic fragments compared with Phanerozoic orogens, suggesting that thick, relatively buoyant, young Archean oceanic lithosphere may have had a structure favoring separation of the uppermost parts during subduction and collisional events.

GREENSTONE BELT GEOMETRY

Geophysical surveys have shown that greenstone belts are mostly shallow to intermediate in depth, extending to 3–15 miles (5–20 km). Some have flat or irregular bases, and granitic rocks intrude many of them. They are not steep synclinal keels. Gravity models consistently indicate that greenstone belts rarely extend to greater than 6 miles (10 km) in depth, and seismic reflection studies show that the steeply dipping structures characteristic of most greenstone belts disappear into a horizontally layered mid to lower crustal structure. Seismic reflection surveys have also proven useful in demonstrating that boundaries between different “belts” in granite-greenstone terrains are in some cases marked by large-scale crustal discontinuities most easily interpreted as sutures or major strike-slip faults.

Just as greenstone belts are distributed asymmetrically on cratons, many have asymmetrical distributions of rock types and structural vergence within them, and in this respect they are much like younger orogenic belts. For example, the eastern Norseman-Wiluna belt in the Yilgarn craton contains a structurally disrupted and complex association of oceanic-type mafic and island arc-type volcanic rocks, whereas the western Norseman-Wiluna belt contains disrupted rocks of predominantly oceanic affinity. In other belts it is typical to find juxtaposed rocks from different crustal levels and facies that were originally laterally separated. One of the long-held misconceptions about the structure of greenstone belts is that they simply represent steep synclinal keels of volcanic and sedimentary rocks squeezed between diapiric granitoids. Where studied in detail, there is a complete lack of continuity of strata from either side of the supposed syncline, and the structure is much more complex than the pinched-synform



Map showing the main structural elements of greenstone belts: dark green are granites; light green are greenstones; tan are metasediments; red lines are foliations *(modified from T. Kusky, and J. Vearncombe, 1997)* model predicts. The structure and stratigraphy of greenstone belts will be unraveled only when "stratigraphic" methods of mapping are abandoned and techniques commonly applied to gneissic terrains are used for mapping greenstone belts. Greenstone belts should be divided into structural domains, defined by structural style, metamorphic history, distinct lithological associations, and age groupings where these data are available.

One of the most remarkable features of Archean greenstone belts is that structural and stratigraphic dips are in most cases very steep to vertical. These steep dips are evidence of the intense deformation that these belts have experienced, although mechanisms of steepening may be different in different examples. Some belts, including the central Slave Province in Canada and the Norseman-Wiluna belt of Western Australia, appear to have been steepened by a series of thrust faults stacking the rocks end over end. Successive offscraping of the greenstone from oceanic crust in thrust sheets steepens rocks toward the interior of the thrust belt. In other cases intrusions have steepened greenstone belt rocks on the margins of plutons and batholiths. Examples of this mechanism are found in the Pilbara craton of Australia and northern Zimbabwe cratons of Africa. Shortening of the entire crust appears to be an important steepening mechanism in other examples, such as in the Theespruit area of the Barberton Belt of southern Africa's Kaapvaal craton. Tight to isoclinal upright folding, common in most greenstone belts, and fold interference patterns are responsible for other steep dips. In still other cases rotations incurred in strike-slip fault systems (e.g., Norseman-Wiluna belt Superior Province) and on listric normal fault systems (e.g., Quadrilatero Ferrifero, San Francisco craton) may have caused local steepening of greenstone belt rocks. These are the types of structures present throughout Phanerozoic orogenic belts.

STRUCTURAL V. STRATIGRAPHIC THICKNESS OF GREENSTONE BELTS

Many studies of the "stratigraphy" of greenstone belts have assumed that thick successions of metamorphosed sedimentary and volcanic rocks occur without structural repetition, and that they have undergone relatively small amounts of deformation. As fossil control is virtually nonexistent in these rocks, stratigraphic correlations are based on broad similarities of rock types and poorly constrained isotopic dates. In pre-1980 studies it was common to construct single stratigraphic columns that were 6–12 miles (10–20 km) or more thick, but recent advances in the recognition of thin fault zones and precise geochronological ages documenting older rocks thrust over younger rocks in the stratigraphy of some belts makes reevaluation of these thicknesses necessary. Intact stratigraphic sections more than a couple of miles thick in greenstone belts are rare. Further mapping needs to be structural, based on defining domains of similar structure, lithology, and age, rather than lithological, attempting to correlate multiply-deformed rocks across large distances.

An observation of great importance for interpreting the significance of supposed thick stratigraphic sections in greenstone belts is that there is an apparent lack of correlation between metamorphic grade and inferred thicknesses of the stratigraphic pile. If the purported 6–12-mile (10–20-km) thick sequences were real stratigraphic thicknesses, an increase in metamorphic grade would be detectable with inferred increase in depth. Because this is not observed, the thicknesses must be tectonic and thus reflect stratigraphic repetition in an environment such as a thrust belt or accretionary prism, where stratigraphic units can be stacked end-on-end, with no increase in metamorphic grade in what would be interpreted as stratigraphically downward. Other mechanisms by which apparent stratigraphic thicknesses may be increased are by folding, erosion through listric normal fault blocks, and progressive migration of depositional centers.

GREENSTONE-GNEISS CONTACT RELATIONSHIPS

An important problem in many greenstone belt studies is determining the original structural relationships between greenstone belts and older gneiss terrains. In pre-1990 studies the significance of early thrusting along thin fault zones went unrecognized, leading to a widespread view that many greenstone belts simply rest in depositional contact over older gneisses, or that the older gneisses intruded the greenstone belt. While this may be the case in a few examples, it is difficult to demonstrate, and the classic areas in which such relationships were supposedly clearly demonstrable have recently been shown to contain significant early thrust faults between greenstones and older sedimentary rocks that rest unconformably over older gneisses. Such is the case at Steep Rock Lake in the Superior Province, at Point Lake and Cameron River in the Slave Province, in the Theespruit type section of the Barberton greenstone belt, at Belingwe, Zimbabwe, and in the Norseman-Wiluna belt.

The Norseman-Wiluna, Cameron River, and Point Lake greenstone belts contain up to 1,640-foot (500-m) wide metamorphic aureoles at their bases. The aureoles contain upper-amphibolite facies assemblages, in contrast to greenschist and lower-amphibolite facies assemblages in the rest of the greenstone belts. The aureoles have mylonitic, gneissic, and schistose fabrics parallel to the upper contacts with the greenstone belts, and are locally partially melted, forming granitic anatectites. The aureole at the base of the Norseman-Wiluna belt is an early shear zone structure related to the thrusting of the greenstone belt over the older gneisses. This fault zone is overprinted by greenschist facies metamorphic fabrics and two episodes of regional folding, the second of which is the main regional deformation event and is associated with a strong cleavage. On Cameron River and Point Lake in the Slave Province, the aureoles represent early thrust zones related to the tectonic emplacement of the greenstone belts over the gneisses. Amphibolite-facies mylonites were derived through deformation of mafic and ultramafic rocks at the bases of the greenstone belts, which are largely at greenschist facies. The broad field-scale relationships in these cases are also similar to those found in metamorphic aureoles attached to the bases of many obducted ophiolites.

STRUCTURAL ELEMENTS OF GREENSTONE BELTS

The earliest structures found in greenstone belts formed during deposition of the rocks. In most greenstone belts the mafic volcanic/plutonic section is older than the sedimentary section, so structures that formed during formation of the igneous rocks are older in the magmatic than in the sedimentary rocks. Unequivocal evidence is lacking for large-scale deformation of the igneous rocks of greenstone belts during their deposition. Structures of this generation typically include broken pillow lavas grading into breccias and possible slump folds and faults in inter-pillow sedimentary horizons.

Two types of early shear zones active before regional contractional deformation have been described from the Jamestown ophiolite in the Barberton greenstone belt of southern Africa. The first are low-angle normal faults located along the lower contacts of the ophiolite-related cherts (so-called Middle Marker); they cause extensive brecciation and alteration of adjacent mafic rocks. The faults and adjacent cherts are cut by subvertical mafic rocks of the Onverwacht Group, showing that these faults were active early, during the formation of the ophiolitic Onverwacht Group. The second type of early faults in the Barberton greenstone belt occur in both the plutonic and the extrusive igneous parts of the Jamestown ophiolite, and may represent steepened continuations (root zones) of the higher-level extensional faults, or they may represent transform faults. Other possible examples of early extensional faults have been described from the Cameron River and Yellowknife greenstone belts in the Slave Province, and from the Proterozoic Purtuniq ophiolite in the Cape Smith Belt of the Ungava Orogen. In the Purtuniq ophiolite early sinuous shear zones locally separate sheeted dikes from mafic schists, causing rotation of the dike complex. In other places dikes intrude this contact, showing that the shear zones are early features. Although not explicitly interpreted in this way, these shear zones may be related to block faulting in the region of the paleoridge axis.

Detailed mapping in a number of greenstone belts has revealed early thrust faults and associated folds. Most do not have any associated regional metamorphic fabric or axial planar cleavage, making their identification difficult without detailed structural mapping. Examples are known from the Zimbabwe and Kaapvaal cratons, the Yilgarn craton, the Pilbara craton, the Slave Province, and the Superior Province. In these cases it is apparent that early thrust faulting and associated folding is responsible for the overall distribution of rock types in the greenstone belts, and also accounts for what were in some cases previously interpreted as enormously thick stratigraphic sequences. These early thrust faults are responsible for juxtaposing greenstone sequences with older gneissic terrains. Few of these early thrust faults are easy to detect; they occupy thin, poorly exposed structural intervals within the greenstone belts, some are parallel to internal stratigraphy for many miles, and most have been reoriented by later structures. In many greenstone belts there are numerous layer-parallel fault zones, but their origin is unclear because they are not associated with any proven stratigraphic repetition or omission. Although it is possible that these faults are thrust, strike-slip, or normal faults, the evidence so far accumulated in the few well-mapped examples supports the interpretation that they are early thrust faults. In some cases late intrusive rocks have utilized the zone of structural weakness provided by the early thrusts for their intrusion.

Emplacement of the early thrust and fold nappes is typically not associated with any strong fabric or cleavage development or any regional metamorphic recrystallization, making recognition of these early structures even more difficult. Delineation of early thrusts depends critically on very detailed fieldwork with particular attention paid to details of the structural geology. Determining the sense of tectonic transport of early nappes is critical for tectonic interpretation, but is also one of the most elusive goals because of the weak development of critical lineations and reorientation of the earliest fabric elements by younger structures. Kinematic studies of early shear zones have received far less attention than they deserve in Archean greenstone belts.

Folds are in many cases the most obvious outcrop to map-scale structures in greenstone belts. Several different generations of folding are typical, and fold interference patterns are commonplace.

Some greenstone belts show a progression from early recumbent folds (flat-lying folds, associated with thrust/nappe tectonics), through two or more phases of tight to isoclinal upright folds, which are associated with the most obvious mesoscopic and microscopic fabric elements and metamorphic mineral growth. One or more generations of late open folds or broad crustal arches with associated crenulation cleavages also affect many greenstone belts. Fold interference patterns most typically reflect the geometry of second- and third-generation fold (F_2 and F_3) structures because they have similar amplitudes and wavelengths; F_1 recumbent folds are best recognized by reversals in younging directions (the direction toward the original tops of beds), or downward-facing F_2 and F_3 folds.

Relationships of individual fold generations to tectonic events is poorly understood in many greenstone belts, and the orientations of stresses that formed the folds are poorly constrained, largely because of uncertainties associated with correctly unraveling superimposed folding events. The relative importance of "horizontal" versus "vertical" tectonics has been debated, in part because it is difficult to distinguish granite-cored domes produced by the interference of different generations of folds from domes produced by diapirism, or the rising of granite as a crystal-rich magma. Two generations of upright folds with similar amplitudes and wavelengths produce a dome and basin fold interference pattern that closely resembles a pattern formed by intruding granite domes.

Many granite-greenstone terrains are cut by late-stage strike-slip faults, some of which are reactivated structures that may have been active at other times during the history of individual greenstone belts. Strike-slip dominated structural styles are found in the Superior Province, the Yilgarn craton, the Pilbara craton, and southern Africa.

Large-scale lineaments of the Norseman–Wiluna Belt near Kalgoorlie and Kambalda, Australia, show late reverse motion related to regional oblique compression. But their length is often greater than 62 miles (100 km), and consistent indicators of a sinistral component of motion suggest that they are dominantly strike-slip structures. These large-scale structures were present through the deformation history that bound domains within which unique structures are developed. These major faults may represent reactivation of terrane boundaries, since they separate zones of contrasting stratigraphy and structure.

The Superior Province consists of a number of fault-bounded subprovinces containing rocks of different lithological associations, ages, and structural and metamorphic histories. The greenstone terrains consist of several types, including some dominated by oceanic-type igneous rocks, island arc-type volcanic complexes, and continental-style volcanic rocks with associated fluvial deposits. Belts of variably metamorphosed muddy sandstones called turbidites, interpreted as accretionary prisms, are younger than and separate from individual volcanic belts. Most of the greenstone belts are progressively younger toward the south in the central parts of the Superior Province. This observation together with the contemporaneity of deformation events within individual belts suggests that the Superior Province represents an amalgam of oceanic crust and plateaus, island arcs, continental margin arcs, and accretionary prisms, brought together by dextral oblique subduction, which formed the major subprovince-bounding strike-slip faults. Continued late strike-slip motion on some of the faults localized alkalic volcanic and fluvial sedimentary sequences in pull-apart basins on some of these strike-slip faults.

In the Vermillion district of the southern Superior Province the deformation history begins with early nappe-style structures overprinted by the "main" fabric elements related to dextral strike slip along with thrusting. This sequence of structural development is interpreted to reflect dextral-oblique accretion of island arcs and microcontinents of the southern Superior Province. A combination of north-south shortening together with dextral simple shear led to the juxtaposition of zones with constrictional and with flattening strains. Geologists previously interpreted the constrictional strains in this area to be a result of "squeezing" between batholiths, necessitating reevaluation of similar theories for the origin of prolate strains in numerous other greenstone belts.

In some cases strike-slip faults have played an integral role in the localization and generation of greenstone belts in pull-apart basins between the strike-slip faults. Several strike-slip fault systems associated with the formation of greenstone belts in pull-apart basins are known from the Pilbara craton. The Lalla Rookh and circa 2.95 billion-year-old Whim Creek belts are interpreted as "second-cycle greenstones," because they were deposited in strike-slip–related pull-apart basins that formed in already complexly deformed and metamorphosed circa 3.5–3.3 billion-year-old rocks of the Pilbara craton. Thus although these fault systems form an integral part of the structural evolution of the Pilbara craton, they postdate events related to initial formation of the granite-greenstone terrain. One problem that future studies of greenstone belt structure should address is an understanding of the nature of the transition from brittle to ductile strains in pull-apart regions along strike-slip fault systems, such as those of the Pilbara.

Major late-stage strike-slip fault zones cut many cratons, but few have well-constrained kinematic or metamorphic histories. An exception is the 186-mile (300-km) long Koolyanobbing shear zone in the Southern Cross Province of the Yilgarn craton. The Koolyanobbing shear is a 4–9-mile (6–15-km) wide zone with a gradation from foliated granitoid, through protomylonite, mylonite, to ultramylonite, from the edge to the center of the shear zone. Shallowly plunging lineations and a variety of kinematic indicators show that the shear zone is a major sinistral fault, but regional relationships suggest that it does not represent a major crustal boundary or suture. Fault fabrics both overprint and appear coeval with late stages in the development of the regional metamorphic pattern, suggesting that the shear zone was active around 2.7–2.65 billion years ago.

LATE EXTENSIONAL COLLAPSE, DIAPIRISM, DENUDATION

It is widely recognized that in Phanerozoic orogens, late stages of orogenic development are characterized by extensional collapse of structurally overthickened crust. In granite-greenstone terrains late stages of mountain building and orogenesis are characterized by the intrusion of abundant granitic magmas, with chemical signatures indicative of crustal melting. The intrusion of late granitic plutons in greenstone terrains may be related to rapid uplift and crustal melting accompanying extension in the upper crust. Early plutons of the tonalite-trondhjemite-gabbro-granodiorite suite are generated in an island arc setting, and are in turn intruded by continental margin arc magmas after the primitive arcs collide and form larger continental fragments. When plate collision causes further crustal thickening, melting of the deep crust produces thin diapiric plutons that rise partway through the crust but crystallize before rising very far, as they do not contain enough heat to melt their way through the crust. The crustal sections in these collisional orogens gravitationally collapse when the strength of quartz and olivine can no longer support the topography. Decompression in the upper mantle and lower crust related to upper-crustal extension generates significant quantities of basaltic melts. These basaltic melts rise and partially melt the lower or middle crust, becoming more silicic by assimilating crustal material. The hybrid magmas thus formed intrude the middle and upper crust, forming the late to post-kinematic granitoid suite so common in Archean granite-greenstone terrains. If the time interval between crustal thickening and gravitational collapse is short, then magmas related to decompressional melting may quickly rise up the partially solidified crystal/mush pathways provided by the earlier plutons generated during the crustal thickening phases of orogenesis. Such temporal and spatial relationships easily account for the common occurrence of composite and compositionally zoned plutons in Precambrian and younger orogenic belts.

See also African geology; Archean; continental crust; craton; North American geology; ophiolites; Precambrian.

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Grenville province and Rodinia

At several times in the history of the planet, most of the continental landmasses have aggregated or joined together to form large supercontinents. The most recent of these was the fairly familiar supercontinent of Pangaea, which contained most of the planet's continents between 300 and 200 million years ago. Before that, the supercontinent of Gondwana formed at about 570 million years ago and lasted only a short geological time (the exact amount is still under debate and investigation). As we explore further back in geological time, the evidence for older supercontinents becomes harder and harder to interpret. Despite this, in the past decade geologists have been able to reconstruct an older supercontinent, known as Rodinia, that formed about 1 billion years ago and broke up around 700 million years ago.

The Grenville province is the youngest region of the Canadian shield; it is outboard of the Labrador, New Quebec, Superior, Penokean, and Yavapai-Mazatzal provinces. It is the last part of the Canadian shield to experience a major deformational event, this being the Grenville Orogeny, which was responsible for forming many folds and faults throughout the entire region during the amalgamation of numerous continents to form the supercontinent of Rodinia. The other ancient, highly eroded mountain belts around the world that formed during the collision of the other continents to form Rodinia have also become known as Grenvillian belts, named after the excellent type exposures of deeply eroded mountain belts of this age in the Grenville province. The Grenville province has an aerial extent of approximately 600,000 square miles (1,000,000 km^2). The subterranean extent of Grenville rocks, however, is much greater in area. Phanerozoic rocks cover their exposure from New York State down the length of the Appalachian Mountains and into Texas.

The Grenville province formed on the margin of the continent of Laurentia (an early or immature stage in the development of North America) in the middle to late Proterozoic. The rocks throughout the province represent a basement and platform sedimentary sequence intruded by igneous rocks. Subsequent to this intrusive event in the late Proterozoic, the entire region underwent high-grade metamorphism and was complexly deformed. But before this high-grade metamorphic event, the rocks of the Grenville province experienced multiple pulses of metamorphism and deformation, including the Elsonian (1,600–1,250-million-year-old) and the Elzevirian (1,250–1,200-million-year-old). Orogenies. The Ottawan Orogeny was the last and most intense in the Grenville province, culminating 1.1 billion years ago, and overprinting much of the earlier tectonic history. This has made it difficult for geologists to describe the earlier orogenies and also to determine the tectonic evolution of the Grenville province. For these reasons, the term *Ottawan Orogeny* is usually used synonymously with the term *Grenville Orogeny*.

The Grenville province is subdivided into numerous subprovinces including the central gneiss belt (CGB), central metasedimentary belt (CMB), and central granulite terrane (CGT), and one major structural feature: the Grenville front (GF).

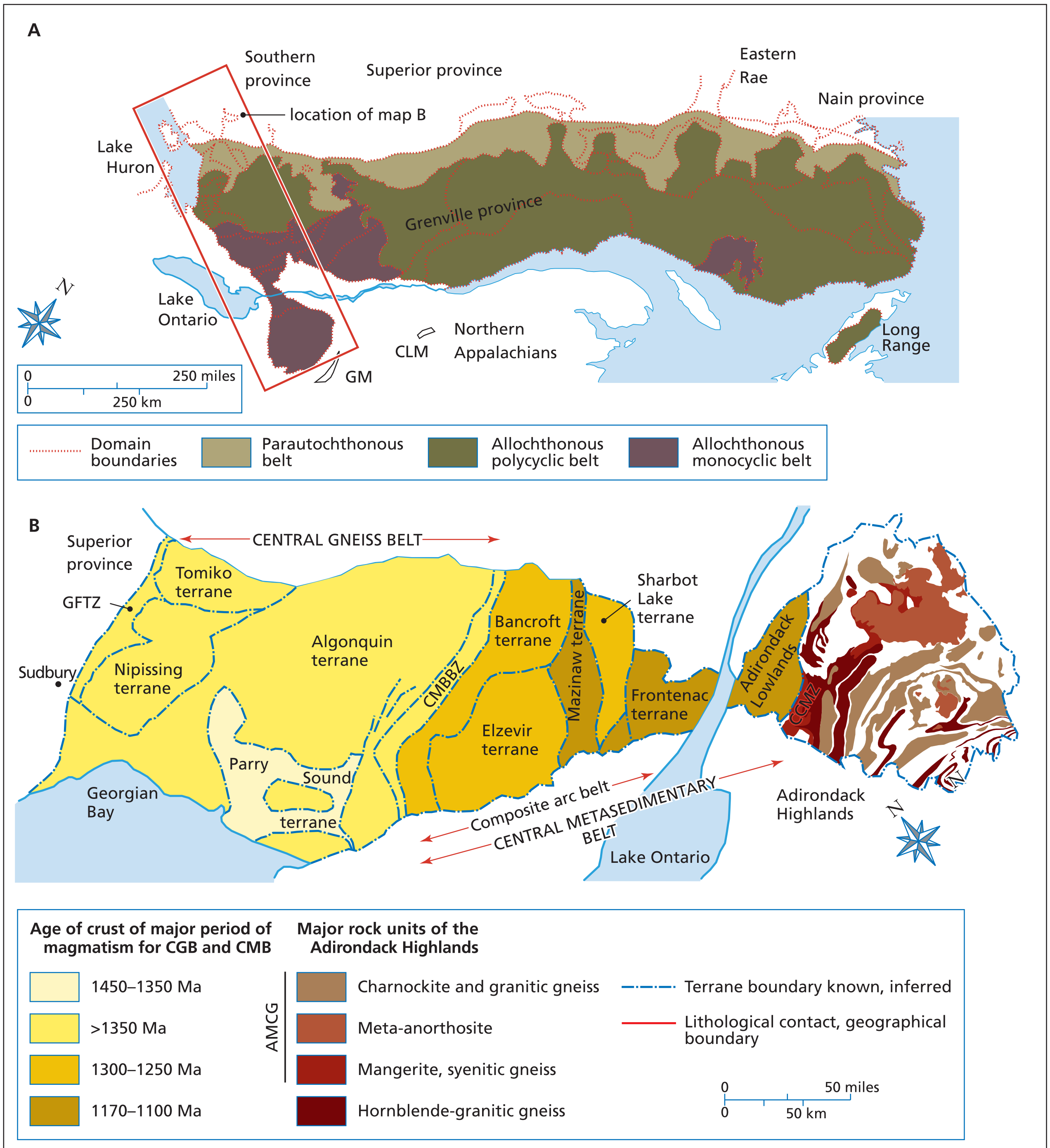
The central gneiss belt (CGB) is located in the western part of the Grenville province and contains some of the oldest rocks found in the province. The majority of the rocks are 1.8–1.6 billion-year-old gneisses intruded by 1.5–1.4 billion-year-old granitic and monzonitic plutons. Both the metasedimentary and the igneous rocks of the CGB are metamorphosed from upper amphibolite and locally granulite facies. The CGB is bounded by the Grenville front to the northwest and lies in tectonic contact with the central metasedimentary belt to the southeast. The dominant structural trend is northeast, but changes to the northwest near Georgian Bay. The CGB has been divided into smaller terranes including the Nipissing, Algonquin, Tomiko, and Parry Sound, based on lithology, metamorphic grade, and structures, namely, shear zones. These terranes are considered to be mainly parautochthonous (meaning that they have not traveled far from their place of formation) terranes. The shear zones that separate the various terranes contain kinematic indicators that suggest northwest directed tectonic transport, and tectonic transport is thought to have occurred between 1.18 and 1.03 billion years ago.

The Nipissing terrane is located in the western portion of the central gneiss belt. Part of the Nipissing terrane occupies a region known as the Grenville front tectonic zone (GFTZ), an area that lies within 30 miles (50 km) of the Grenville front. The lithologies here are strongly deformed with northeast-striking foliations and zones of cataclasis and moderately plunging southeast lineations. The heterogeneous gneisses of the Nipissing terrane fall into two categories: Archean and Lower Proterozoic migmatitic gneisses that are likely reworked units of the Southern and Superior provinces and Middle Proterozoic metasedimentary gneiss. These rocks were intruded by 1.7 and 1.45 billion-year-old granitic plutonic rocks, both of which are less deformed than the host rocks. Postdating this intrusive event, the region underwent high-grade metamorphism, experiencing temperatures of 1,200°F–1,280°F (650°C–750°C) and pressures of 8.0–8.5 kilobars.

The Tomiko terrane is located in the extreme northwestern portion of the central gneiss belt. The most striking aspect of the Tomiko terrane is the relative abundance of metasedimentary rocks, but it also contains metamorphosed granitic rocks that are Middle Proterozoic in age. The Tomiko terrane is allochthonous (far-traveled) with respect to the Nipissing terrane. Evidence to support this is the distinct detrital zircon population in the Tomiko metaquartzites, dated at 1,687 million years old. This is in sharp contrast to the metaquartzites of the Nipissing terrane, where the detrital zircons are Archean to Lower Proterozoic in age. This suggests that the Nipissing terrane was already adjacent to the Superior province at the time of the Nipissing quartzite formation. Further evidence for the allochthonous nature of the Tomiko terrane is the presence of iron formations in the Tomiko terrane, which are not present elsewhere in the CGB. The metamorphic conditions experienced by the Tomiko terrane are temperatures of fewer than 1,290°F (700°C) and pressures of 6.0–8.0 kilobars.

The Algonquin terrane, the largest terrane in the CGB, consists of numerous domains. The rocks in this terrane are meta-igneous quartzo-feldspathic gneisses and supracrustal gneisses. Generally, the foliations strike northeast and dip to the southeast; down-dip stretching lineations are common. The southern domains have been interpreted as thrust sheets with a clear polarity of southeasterly dips, and the entire Algonquin terrane may be parautochthonous. The metamorphic temperatures and pressures range from 1,240°F–1,520°F (670°C–825°C) and 7.9–9.9 kilobars, respectively.

The Parry Sound terrane, the most studied terrane in the CGB, is located in the south-central portion of the CGB and contains large volumes of mafic rock, marble, and anorthosite. The age of the Parry Sound terrane ranges from 1,425 to 1,350 million years. Both the lithologies and the age of the Parry



Maps compiled from McLelland and Isachsen, 1985; Rivers, et al., 1989; McLelland, et al., 1996; Carr, et al., 2000.

(A) Tectonic subdivisions of the Grenville province according to the classification of Toby Rivers (1989) and Carr, et al. (2000), showing also the older domain boundaries of Wynne-Edwards (1972) and others; (B) Terranes and shear zones of the central gneiss belt (CGB), the central metasedimentary belt (CMB), and major geological features of the Adirondack Highlands. Abbreviations as follows: BCS-Baie Comeau segment; CCMZ-Carthage-Colton mylonite zone; CLM-Chain Lakes massif; CMBBZ-central metasedimentary belt boundary zone; CGB-central gneiss belt; CGT-central granulite terrane; EGP-eastern Grenville province; GFTZ-Grenville Front tectonic zone; GM-Green Mountains.

Sound terrane are different from the rest of the CGB. Not surprisingly, therefore, this terrane is considered as allochthonous and overlying the parautochthonous Algonquin domains. Because the Parry Sound terrane is completely surrounded by the Algonquin terrane, structurally it is considered a klippe. The metamorphic conditions reached by the Parry Sound terrane are in the range of 1,200°F–1,470°F (650°C–800°C) and 8.0–11.0 kilobars.

The central metasedimentary belt (CMB) has a long history of geologic investigation. One of the reasons is the abundance of metasedimentary rocks, which makes it a prime target for locating ore deposits. The CMB was originally named the Grenville series by Sir William Logan in 1863 for an assemblage of rocks near the village of Grenville, Quebec, and is the source of the name for the entire Grenville province. Later, the Grenville series achieved supergroup status, but presently *Grenville Supergroup* is a term limited to a continuous sequence of rocks within the CMB.

The CMB contains Middle Proterozoic metasediments that were subsequently intruded by syn-, late-, and post-tectonic granites. The time of deposition is estimated to have been from 1.3 to 1.1 billion years ago, with the bulk of the material having been deposited before 1.25 billion years ago. After their deposition, the rocks of the CMB underwent deformation and metamorphism from in the Elzevirian Orogeny (1.19–1.06 billion years ago). The effects of the Elzevirian Orogeny were all but wiped out by the later Ottawan Orogeny, which deformed and metamorphosed the rocks to middle-upper amphibolite facies. The CMB contains five distinct terranes: Bancroft, Elzevir, Sharbot Lake, Mazinaw, and Frontenac. The Frontenac is correlative with the Adirondack Lowlands.

The Bancroft terrane is located in the northwestern portion of the CMB. The Bancroft is dominated by marbles but also contains nepheline-bearing gneiss and granodioritic orthogneiss metamorphosed to middle through upper amphibolite facies. The Bancroft terrane contains complex structures, such as marble breccias and high-strain zones. The orthogneiss occurs in thin structural sheets, suggesting that it may occur in thrust-nappe complexes. The thrust sheets generally dip to the southeast with dips increasing toward the dip direction. Rocks of the Bancroft terrane possess a well-developed stretching lineation that also plunges in the southeast direction. Both of these structural orientations suggest northwest directed tectonic transport.

The Elzevir terrane, located in the central portion of the CMB, is known for containing the classic Grenville Supergroup. The Elzevir is composed of 1.30–1.25-billion-year old metavolcanics and metasediments, intruded by 1.27-billion-year-old tonalitic plutons ranging in composition from gabbro to syenite. The largest of these calc-alkaline bodies is the Elzevirian batholith. The calc-alkaline signature of the batholith suggests that it may have been generated in an arc-type setting. The Elzevir terrane also contains metamorphic depressions, areas of lower metamorphic grade, such as greenschist to lower amphibolite facies. These depressions may be related to the region's polyphase deformation history, and in contrast to surrounding high-grade terranes, they contain sedimentary structures enabling the application of stratigraphic principles to determine superposition.

The Mazinaw terrane was once mapped as part of the Elzevir terrane; it also contains some of the classic Grenville Supergroup marbles and the Flinton Group. The rocks encountered here are marbles, calc-alkalic metavolcanic and clastic metasedimentary rocks. The Flinton Group is derived from the weathering of plutonic and metamorphic rocks found in the Frontenac terrane. Furthermore, the complex structural style of the Mazinaw terrane is similar to the Frontenac and the Adirondack Lowlands.

The Sharbot Lake terrane was once mapped as part of the Frontenac terrane but is now considered a separate terrane. The Sharbot Lake principally contains marbles and metavolcanic rocks intruded by intermediate and mafic plutonic rocks and may represent a strongly deformed and metamorphosed carbonate basin. Metamorphic grade ranges from greenschist to lower amphibolite. The lithologies, metamorphic grade, and lack of exposed basement rocks to the Sharbot Lake terrane imply that these rocks may be correlative with the Elzevir terrane.

The Frontenac terrane is located in the southeastern portion of the CMB. This terrane extends into the Northwest Lowlands of the Adirondack Mountains. The Frontenac terrane is composed of marble with pelitic gneisses and quartzites. The relative abundances of the gneisses and quartzites increase toward the southeast, while the relative abundances of metavolcanic rocks and tonalitic plutons decrease in the same direction. A trend also exists in the metamorphic grade from northwest to southeast. In the northwest the metamorphic grade ranges from lower amphibolite to upper amphibolite-granulite facies but then decreases in the southeast to amphibolite facies. Rock attitudes also change, dipping southeast in the northwest, to vertical in the central part, to the northwest in the Northwest Lowlands.

Throughout the CMB, large-scale folds are present. These folds indicate crustal shortening. More important, however, is the recognition of main structural breaks that lie both parallel to and within the CMB. The structural breaks are marked by narrow zones of highly attenuated rocks, such as mylonites. The Robertson Lake mylonite zone (RLMZ), one such structural break, lies between the Sharbot Lake terrane and the Mazinaw terrane. The RLMZ has been interpreted as a low-angle thrust fault and also as a normal fault caused by unroofing.

To the east of the central metasedimentary belt lies the central granulite terrane. These two subprovinces are separated by the Chibougamau-Gatineau Lineament (CGL), a wide mylonite zone. The fact that the CGL is well-defined on aeromagnetic maps suggests that it is a crustal-scale feature. The CGL roughly trends northeast-southwest, where it ranges from about 10 feet (a few meters) to more than four miles (7 km) wide. The CGL may be correlative with the Carthage Colton mylonite zone in the Adirondack Mountains of New York State.

The central granulite terrane (CGT), originally named by Canadian geologist H. R. Wynne-Edwards in 1972, is located in the central and southeastern portion of the Grenville province and is correlative with the Adirondack Highlands. The CGT is often referred to as the core zone of the Grenville orogen, and is the site where the majority of the Grenvillian plutonic activity occurred. This subprovince underwent high-grade metamorphism with paleotemperatures ranging up to 1,470°F (800°C) and paleopressures up to 9.0 kilobars. To explain these high pressures and temperatures, a double thickening of the crust is required. For this reason, geologists have suggested that the Grenville province represents a continent/continent collision zone.

The most abundant rock constituent of the central granulite belt is anorthosite. The larger anorthosite bodies are termed massifs, such as the Morin massif. The anorthosites, along with a whole suite of rocks, known as AMCG (anorthosite, mangerite, charnokite, granite) suite, are thought to have intruded at approximately 1,159–1,126 million years ago according to uranium-lead zircon analysis. These dates are in agreement with uranium-lead zircon ages of the AMCG rocks in the Adirondack Highlands (1,160–1,125 million years old). This places their intrusion as postdepositional with the sediments of the CMB and before the Ottawan Orogeny. The anorthosites were emplaced at shallow levels somewhere between the Grenville supergroup and the underlying basement. A major tectonic event such as continental collision must have occurred to produce the high paleotemperatures and paleopressures recorded in the anorthosites.

For the most part the Grenville front (GF) marks the northwestern limit of Grenville deformation and truncates older provinces and structures. The zone is approximately 1,200 miles (2,000 km) long and is dominated by northwest-directed reverse faulting that has been recognized since the 1950s. The GF is recognized by faults, shear zones, and metamorphic discontinuities. Faults, foliations, and lineations dip steeply to the southeast. Interpretation of the Grenville front has changed with time. In the 1960s, with the advent of the theory of plate tectonics, the Grenville front was immediately interpreted as a suture. This suggestion was refuted because Archean age rocks of the Superior craton continue south across the Grenville front, implying that the suture should lie to the southeast of the GF. It is possible that the suture is reworked somewhere in the Appalachian orogen. There are still several unresolved questions about the tectonic nature of the Grenville front, considering that the GF marks the limit of Grenvillian deformation: (1) the adjacent foreland to the northwest contains no evidence of supracrustal assemblages associated with the Grenville orogen, (2) the zone lacks Grenville age intrusives that are prevalent to the southeast, and (3) the front divides older rocks from a belt of gneisses that appear to be their reworked equivalents.

TECTONIC EVOLUTION OF THE GRENVILLE PROVINCE

The tectonic framework of the Grenville province is a topic of considerable debate. Many theories and models have been proposed, although there is no one universally accepted model. Nevertheless, researchers do agree upon some aspects of the tectonic framework, in particular, that the Grenville province represents a collisional boundary. Support for this model includes seismic data and the granulite facies metamorphism, both of which suggest that the crust was doubly thickened during peak deformation and metamorphism.

Crustal thickening can occur by a few mechanisms: thrusting, volcanism, plutonism, and homogeneous shortening. One or a combination of these mechanisms must have occurred in the late Proterozoic to produce granulite facies metamorphism in the Grenville province. Two models that account for similar large tectonic crustal thickening are presently occurring on the Earth's surface.

The first model is fashioned after the Andean-type margin. This model suggests that relatively warm, buoyant oceanic crust is subducted under continental crust. Such a model has several implications. The oceanic crust subducted underneath the South American plate is relatively young. Therefore it has not had a sufficient time interval to cool and become dense. The relative low density of the young oceanic crust resists subduction. Consequently the oceanic crust subducts at a relatively shallow angle. A shallow subduction angle creates a compressional stress regime throughout the margin. This has the effect of crustal shortening accommodated by fore-arc frontal thrusts. The subducting oceanic plate also induces plutonism and volcanism that adds to the crustal thickening process.

The second model is based on the Himalayan Orogen. This model thickens the crust by a continent-continent collision. It is somewhat similar to the Andean model, except continental crust replaces the warm, buoyant oceanic crust. The subducting continental crust resists subduction owing to its buoyancy, causing the subducting continental crust to get tucked under the overriding continental crust. The underriding crust never subducts down into the asthenosphere, but rather underplates the overriding continental crust, hence, crustal thickening. The Andean model may predecede the Himalayan model; therefore a combination of the two models may have worked together to produce the Grenville Orogen in the Proterozoic.

A simplistic tectonic model for the Grenville attempts to explain the broad-scale tectonic processes that may be able to account for the large-scale features. An arc-continent collision was followed by a continent-continent collision in the late Proterozoic, probably involving southeastward directed subduction for the continent-continent collision, consistent kinematics in domain boundary shear zones (in the CGB) that preserve an overall northwesterly direction of tectonic transport, consistent with northwestward stacking of crustal slices.

The calc-alkaline trends of the Elzevirian batholith suggest that this is an island arc-type batholith. Thus the Elzevir terrane was probably an island arc before it collided with North America. The Elzevirian age metamorphism resulted from the collision of the CMB and the CGT. Ultimately, the southeastward subduction along the western CMB margin resulted in a continent-continent collision with the CGB.

Plate reconstructions for the Late Proterozoic are currently an area of active investigation. Recent research in geochronology, comparative geology, stratigraphy, and paleomagnetism has provided a wealth of new information that has proven useful in correlating rocks on a global scale. Geologists use these correlations to determine the temporal and spatial plate configurations for the Late Proterozoic. Such plate reconstructions have provided new insight in the study of the Grenville province.

Advances in geochronology have been the greatest contributor in helping to correlate rocks globally. Field mapping in previously unmapped areas and improved techniques in paleomagnetic determination further help to narrow possible plate configurations. With this knowledge geologists take present-day continents and strip away their margins—more precisely, all post–Grenvillian age rocks—and try to piece together the cratons that may once have been conjugate margins.

In 1991 researchers including Canadian Paul Hoffman now at Harvard University, Eldridge Moores from the University of California, and Ian Dalziel from the University of Texas proposed that a supercontinent existed in the Late Proterozoic. This supercontinent, named Rodinia, was formed by the amalgamation of Laurentia (North America and Greenland), Gondwana (Africa, Antarctica, Arabia, Australia, India, and South America), Baltica, and Siberia. The joining of these plates resulted in collisional events along the Laurentian margins. Geologists believe these orogenic events in the Late Proterozoic produced the Grenvillian belts found throughout the world.

Most Late Proterozoic plate reconstructions place the Canadian Grenville province and Amazonian and Congo cratons in close proximity. Therefore Amazonia and Congo were the probable late Proterozoic continental colliders with the eastern margin of Laurentia, resulting in the Ottawan Orogeny. Evidence supporting this correlation includes the similar isotopic ages of 1.4 billion years of the Grenvillian belts found on the Amazonian and Congo cratons, the same as the Laurentian Grenville province.

Plate reconstructions for the Late Proterozoic are not absolute. Unlike the Mesozoic and Cenozoic, the Proterozoic lacks hard evidence, such as hot spot tracks and oceanic magnetic reversal data, to determine plate motions. Furthermore, definitive sutures that would strongly demonstrate a collisional margin, such as ophiolite sequences and blueschist facies terrains, are deformed and few, making it difficult to determine the exact location of the Grenvillian suture. This may be due to the expansive time interval that ensued, later orogenic events, rifting events, and erosion, all of which help to alter and destroy the geologic record.

Most tectonic models for the Grenville province are broadly similar for the late stages of the evolution of this orogenic belt but differ widely in the early stages. The earliest record of arc magmatism in the central metasedimentary belt comes from the Elzevir terrane or composite arc belt, where ca. 1,350–1,225-million-year-old magmatism is interpreted to represent one or more arc/back arc basin complexes. The Adirondack Lowlands terrane may have been continuous with the Frontenac terrane, which together formed the trailing margin of the Elzevirian arc. Isotopic ages for the Frontenac terrane fall in the range of 1,480–1,380 million years, and between 1,450–1,300 million years for the entire central metasedimentary belt, suggesting that the Elzevirian arc is largely a juvenile terrane. The Elzevirian arc is thought to have collided offshore with other components of the composite arc belt by 1,220 million years ago because of widespread northwestward-directed deformation and tectonic repetition in the central metasedimentary belt at that time. Following amalgamation some interpret the subduction to have stepped southeastward to lie outboard of the composite arc, and dipped westward beneath a newly developed active margin. This generated a suite of ca. 1,207-million-year-old calc-alkaline plutons (Antwerp-Rossie suite) and 1,214 ± 21 million-year-old dacitic volcaniclastics, metapelites, and diorite-tonalitic plutons. Other models suggest that the Adirondack Highlands and Frontenac/Adirondack Lowlands terranes remained separated until 1,170–1,150 million years ago, when the Frontenac and Sharbot Lakes domains were metamorphosed and intruded by plutons.

Many geologists regard the Adirondack Highlands–Green Mountains block to be a single arc complex, based on abundant ca. 1,350–1,250-million-year-old calc-alkaline tonalitic to granodioritic plutons in both areas. The Adirondack Highlands–Green Mountains block may have been continuous with the Elzevirian arc as well, forming one large composite arc complex. Neodymium model ages for the Adirondack Mountains–Green Mountain block fall in the range of 1,450–1,350 Ma, suggesting that this arc complex was juvenile, without significant reworking of older material.

Collision of the Adirondack Highlands–Green Mountain block with Laurentia occurred between the intrusion of the ca. 1,207-million-year-old Antwerp-Rossie arc magmas and formation of the 1,172-million-year-old Rockport-Hyde-School-Wellesley-Wells intrusive suite. This inference is based on the observation that peak metamorphic conditions preceded intrusion of the 1,180–1,150-million-year-old intrusive suite in the Frontenac terrane. Also metamorphic zircon and monazite (presumably dating the collision) from the central metasedimentary belt fall in the range of 1,190–1,180 million years. The Carthage-Colton mylonite zone may represent a cryptic suture marking the broad boundary along which the Adirondack Highlands–Green Mountain block is juxtaposed with Laurentia from a collision that emplaced the Lowlands over the Highlands. Early localized delamination beneath the collision zone may have elevated crustal temperatures and generated crustal melts of the ca. 1,172-million-year-old Rockport and Hyde School granites, and the Wells leucocratic gneiss also belongs to this group. But the present geometry with relatively low-grade rocks of the Lowlands juxtaposed with high-grade rocks of the Highlands suggests that the present structure is an extensional fault that may have reactivated an older structure.

The ca. 1,172-million-year-old collisional granites (Rockport, Hyde School gneiss, Wellesley, Wells) are largely syntectonic, and emplacement of these magmas may have slightly preceded formation of large-scale recumbent nappes including F_1 folds. These large nappes may be responsible for complex map patterns and repetition of units in the CMB and CGT. High-temperature deformation of monzonites in the Robertson Lake shear zone took place at ca. 1,162 million years ago and demonstrated that deformation continued for at least 10 million years after intrusion of the 1,172-million-year-old magmatic suite. Deformation had apparently terminated by 1,160 million years ago, however, as shown by the 1,161–1,157 million-year-old Kingston dikes and Frontenac suite plutons, which cross-cut Elzevirian fabrics and cut the Robertson Lake shear zone.

The widespread monzonitic, syenitic, and granitic plutons (AMCG suite) that intruded the Frontenac terrane in the period from 1,180 to 1,150 million years ago swept eastward across the orogen forming the AMCG suite in the Highlands at 1,155–1,125 million years ago. Jim McLelland, Tim Kusky, and others have suggested that separation of the subcontinental lithospheric mantle that started around 1,180–1,160 million years ago may have proceeded to large-scale delamination beneath the orogen. This would have exposed the base of the crust to hot asthenosphere, causing melting and triggering the formation of the AMCG suite. The 1,165-million-year-old metagabbro units are related to this widespread melting and intrusive event in the Adirondacks.

The culminating Ottawan Orogeny from ca. 1,100–1,020 million years ago in the Adirondacks and Grenville orogen is widely thought to result from the collision of Laurentia with another major craton, probably Amazonia. This collision is one of many associated with the global amalgamation of continents to form the supercontinent Rodinia. The event is associated with large-scale thrusting, high-grade metamorphism, recumbent folding, and intrusion of a second generation of crustal melts associated with orogenic collapse. The putative suture (Carthage-Colton mylonite zone) between the accreted Highlands–Green Mountain block and Laurentia was reactivated as an extensional shear zone in this event, partly accommodating the orogenic collapse and exhumation of deep-seated rocks in the Adirondack Highlands. The relative timing of igneous events and folding in the Adirondacks has shown that the F_2 and F_3 folding events in the southern part of the Highlands postdated 1,165 and predated 1,052 million years ago, demonstrating that these folds, and later generations of structures, are related to the Ottawan Orogeny. The Ottawan Orogeny in this area is therefore marked by the formation of early recumbent fold nappes overprinted by upright folds.

The regional chronology and overprinting history of folding related to the Ottawan Orogeny are generally poorly known. In 1939 Buddington noted isoclinal folds dated ca. 1,149 million years old in the Hermon granite gneiss in the Adirondack Highlands, and very large granulite facies fold nappes have been emplaced throughout the Adirondack region. These folds refold an older isoclinal fold generation, thus are F_2 folds and are related to this regional event. The youngest rocks that show widespread development of fabrics attributed to the Ottawan orogeny are the ca. 1,100–1,090-million-year-old Hawkeye suite, that show "peak" conditions of about 1,470°F at 12–15 miles depth (800°C at 20–25 km depth). These conditions existed from about 1,050 through approximately 1,013 million years ago. Older thrust faults along the CMB boundary zone were reactivated at about 1,080–1,050 million years ago. The latter parts of the Ottawan Orogeny (1,045–1,020 million years ago) are marked by extensional collapse of the orogen, with low-angle normal faults accommodating much of this deformation. Crustal melts associated with orogenic collapse are widespread.

GRENVILLE BELTS AND THE RODINIA SUPERCONTINENT

The Proterozoic saw the development of many continental-scale orogenic belts, many of which have been recently recognized to be parts of global-scale systems that reflect the formation, breakup, and reassembly of several supercontinents. Paleoproterozoic orogens include the Wopmay in northern Canada, interpreted to be a continental margin arc that rifted from North America, then collided soon afterward, closing the young back arc basin. There are many 1.9–1.6-Ga orogens in many parts of the world, including the Cheyenne belt in the western United States, interpreted as a suture that marks the accretion of the Proterozoic arc terrains of the southwestern United States with the Archean Wyoming Province.

The supercontinent Rodinia formed in Mesoproterozoic times by the amalgamation of Laurentia, Siberia, Baltica, Australia, India, Antarctica, and the Congo, Kalahari, West Africa, and Amazonia cratons between 1.1 and 1.0 Ga ago. The joining of these cratons resulted in the terminal collisional events at convergent margins on many of these cratons, including the ca. 1.1–1.0-Ga Ottawan and Rigolet Orogenies in the Grenville Province of Laurentia's southern margin. Globally, these events have become known as the Grenville orogenic period, named after the Grenville orogen of eastern North America. Grenville-age orogens are preserved along eastern North America, as the Rodinia-Sunsas belt in Amazonia, the Irumide and Kibaran belts of the Congo craton, the Namaqua-Natal and Lurian belts of the Kalahari craton, the Eastern Ghats of India, and the Albany-Fraser belt of Australia. Many of these belts now preserve deep-crustal metamorphic rocks (granulites) tectonically buried to 20–25 miles (30–40-km) in depth, then the overlying crust was removed by erosion, forcing the deeply buried rocks to the surface. Since 20–25 miles (28–30 km) of crust still underlies these regions, they may have had double crustal thickness during the peak of metamorphism. Such thick crust is today produced in regions of continent-continent collision, and locally in Andean arc settings. Since the Grenville-aged orogens are so linear and widely distributed, they are generally interpreted to mark the sites of continent-continent collisions where the various cratonic components of Rodinia collided between 1.1 and 1.0 Ga.

See also CONVERGENT PLATE MARGIN PROCESSES; PRECAMBRIAN; STRUCTURAL GEOLOGY; SUPERCONTINENT CYCLES.

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groundwater Groundwater encompasses all of the water contained within spaces in bedrock, soil, and regolith. The volume of groundwater is 35 times the volume of freshwater in lakes and streams, but overall this water accounts for less than 1 percent of the planet's water. Much of the world's population gets its freshwater from the groundwater system, pumping the water from beneath the surface or pulling buckets up from wells dug into the ground. Any body of rock or unconsolidated sediment that can hold and transmit water is known as an aquifer. Units that restrict the flow of water are known as aquitards.

Groundwater comes from rainfall and surface flow, where it seeps into the ground and slowly makes its way downhill toward the sea. Water exists everywhere beneath the ground surface, and most of this occurs within 2,500 feet (750 m) of the surface. The volume of groundwater is estimated to be equivalent to a layer 180 feet (55 m) thick spread evenly over the Earth's land surface. The distribution of water in the ground can be divided into unsaturated and saturated zones. The top of the water table is defined as the upper surface of the saturated zone; below this surface, all openings are filled with water.

Increasingly, groundwater is being used for more functions than simply drinking or watering plants and animals. Water has a high specific heat capacity, meaning that it takes a long time and a lot of heat energy to heat and cool the water. Additionally the insulating effects of the surrounding soil and bedrock means that the groundwater tends to remain at a similar temperature year round, in the low 50°'s Fahrenheit (10–12°C). Based on these properties, engineers are beginning to use water to help heat and cool buildings. During hot weather water is pumped through radiators, cooling the building. In cool weather water is heated, and since it stores heat energy more efficiently than air, energy savings result.

Freshwater is one of the most important resources in the world. Wars are fought over freshwater, and water rights are political issues in places where it is scarce like the American West and the Middle East. Since we live in a world with a finite amount of freshwater and the global population is growing rapidly, it is likely that freshwater will become an increasingly important topic for generations to come. Much of the groundwater in the world is at increasing risk of being contaminated by industrial and human pollutants. Efforts must be undertaken to protect adequately this scarce resource.

America and other nations have realized that groundwater is a vital resource for national survival and are only recently beginning to appreciate that much of the world's groundwater resources have become contaminated by natural and human-aided processes. Approximately 40 percent of drinking water in the United States comes from groundwater reservoirs. About 80 billion gallons of groundwater are pumped out of these reservoirs every day in the United States.

MOVEMENT OF GROUNDWATER

Most of the water under the ground does not just sit there—it is constantly in motion, although rates are typically only an inch or two (2–5 cm) per day. The rates of movement are controlled by the amount of open space in the bedrock or regolith, and how the spaces are connected. The groundwater system also includes water beneath the ground that is immobile, such as water locked in soil moisture, permafrost, plus geothermal and oil-formation water.

Porosity is the percentage of total volume of a body that consists of open spaces. Sand and gravel typically have about 20 percent open spaces, while clay has about 50 percent. The sizes and shapes of grains determine porosity, which is also influenced by how much they are compacted, cemented together, or deformed.

In contrast, permeability is a body's capacity to transmit fluids or to allow the fluids to move through its open pore spaces. Permeability is not directly related to porosity. For instance, all the pore spaces in a body could be isolated from each other (high porosity), and thus the water may be trapped and unable to move through the body (low permeability). Molecular attraction, the force that makes thin films of water stick to objects instead of being forced to the ground by gravity, also affects permeability. If the pore spaces in a material are small, as in a clay layer, then the force of molecular attraction is strong enough to stop the water from flowing through the body. When the pores are large, the water in the center of the pores is free to move.

After a rainfall much of the water stays near the surface, because clay in the near-surface horizons of the soil retains much water due to molecular attraction. This forms a layer of soil moisture in many regions able to sustain seasonal plant growth.

Some of this near-surface water evaporates and is used by plants. Other water runs directly off into streams. The remaining water seeps into the saturated zone, or into the water table. Once in the saturated zone it moves slowly by percolation, from high areas to low areas, under the influence of gravity. These lowest areas are usually lakes or streams. Many streams form where the water table intersects the surface of the land.

Once in the water table the paths that individual particles follow vary. The transit time from surface to stream may vary from days to thousands of years along a single hillside. Water can flow upward because of high pressure at depth and low pressure in streams.

THE GROUNDWATER SYSTEM

Groundwater is best thought of as a system of many different parts, some of which act as conduits and reservoirs, and others that serve as offramps and onramps into the groundwater system.

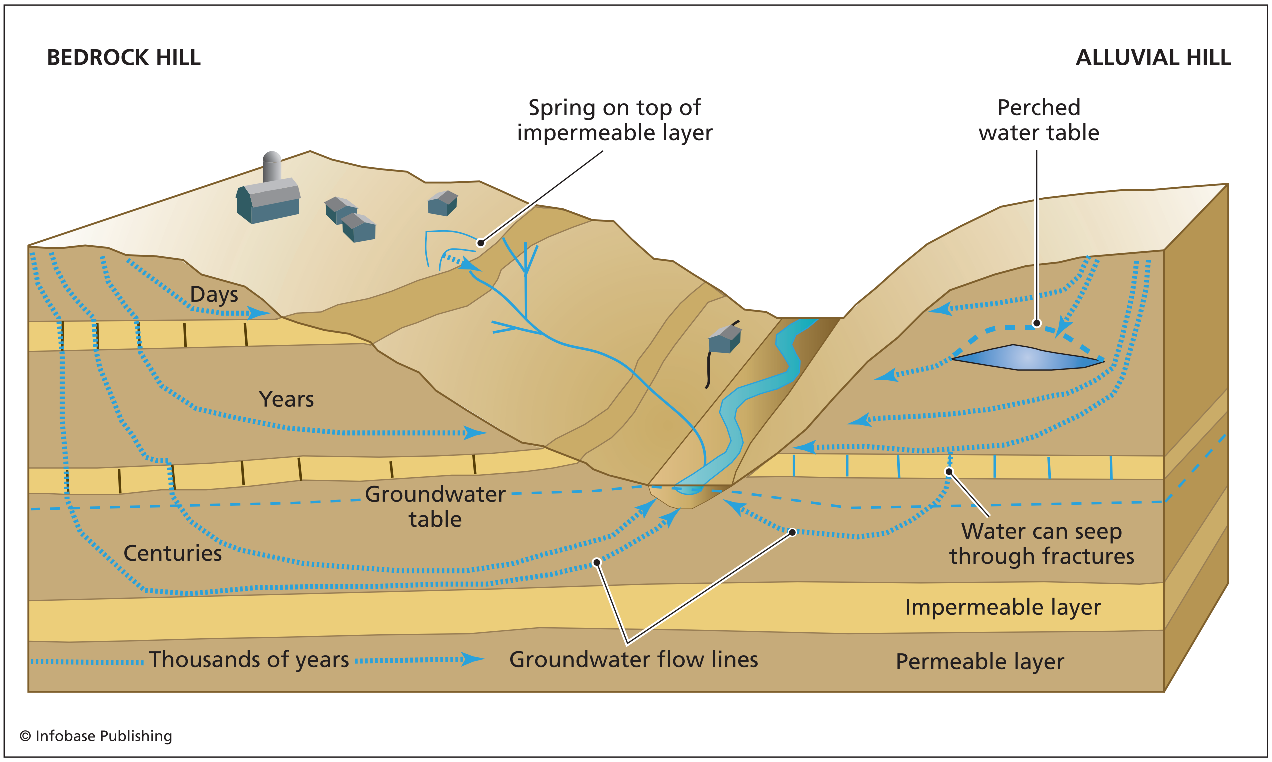
Recharge areas are where water enters the groundwater system, and discharge areas are where water leaves the groundwater system. In humid climates recharge areas encompass nearly the land's entire surface (except for streams and floodplains), whereas in desert climates recharge areas consist mostly of the mountains and alluvial fans. Discharge areas consist mainly of streams and lakes.

The level of the water table changes with different amounts of precipitation. In humid regions it reflects the topographic variation, whereas in dry times or locations it tends to flatten out to the level of the streams and lakes. Water flows faster when the slope is greatest, so groundwater flows faster during wet times. The fastest rate of groundwater flow observed in the United States is 800 feet per year (250 m/yr).

Aquifers include any body of permeable rock or regolith saturated with water through which groundwater moves. Gravel and sandstone make good aquifers, as do fractured rock bodies. Clay is so impermeable that it makes bad aquifers, and typically forms aquicludes that stop the movement of water.

Springs are places where groundwater flows out at the ground surface. They can form where the ground surface intersects the water table or at a vertical or horizontal change in permeability, such as where water in gravels on a hillslope overlays a clay unit and the water flows out on the hill along the gravel/clay boundary.

Water wells fill with water simply because they intersect the water table. The rocks below the surface are not always homogeneous, however, which can result in a complex type of water table known as a perched water table. Perched water tables result from impermeable bodies in the subsurface that create bodies of water at elevations higher than the main water table.



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Schematic diagram of the groundwater system. Water enters the system on hillslopes and emanates lower on hills as springs and in effluent streams.

WATER WELLS AND USE OF GROUNDWATER

Most wells fill with water simply because they intersect the water table. But the rocks below the surface are not always homogeneous, which can result in a complex type of water table know as a perched water table. These result from discontinuous bodies in the subsurface, which create bodies of water at elevations higher than the main water table.

Aquifers

Aquifers are any body of permeable rock or regolith saturated with water through which groundwater moves. The term *aquifer* is usually reserved for rock or soil bodies that contain economical quantities of water that are extractable by existing methods. The quality of an aquifer depends on two main qualities, porosity and permeability. Porosity is a measure of the total amount of open void space in the material. *Permeability* refers to the ease at which a fluid can move through the open-pore spaces, and depends in part on the size, shape, and how connected individual pore spaces are in the material. Gravels and sandstone make good aquifers, as do fractured rock bodies. Clay is so impermeable that it makes bad aquifers and typically forms aquicludes, which stop the movement of water.

There are several main types of aquifers. In uniform, permeable rock and soil masses aquifers form as a uniform layer below the water table. In these simple situations wells fill with water simply because they intersect the water table. But the rocks below the surface are not always homogeneous and uniform, which can result in a complex type of water table know as a perched water table. These result from discontinuous impermeable rock or soil bodies in the subsurface, which create domed pockets of water at elevations higher than the main water table, resting on top of the impermeable layer.

When the upper boundary of the groundwater in an aquifer is the water table, the aquifer is said to be unconfined. In many regions, a permeable layer, typically a sandstone, is confined between two impermeable beds, creating a confined aquifer. In these systems water enters the system only in a small recharge area, and if this is in the mountains, then the aquifer may be under considerable pressure. This is known as an artesian system. Water that escapes the system from the fracture or well reflects the pressure difference between the elevation of the source area and the discharge area (hydraulic gradient), and rises above the aquifer as an artesian spring or artesian well. Some of these wells have made fountains that have spewed water 200 feet (60 meters) high. One example of an artesian system is that in Florida, where water enters in the recharge area, and is released near Miami about 19,000 years later.

Big Spring, Missouri *(Jose Azel/Aurora/Getty Images)*

Fracture Zone Aquifers

Hydrologists, geologists, and municipalities in need of water have increasingly appreciated that significant quantities of fresh water is stored in fractures within otherwise impermeable crystalline rocks beneath the ground. Many buried granite and other bedrock bodies are cut by many fractures, faults, and other cracks, some of which may have open spaces along them. Fractures at various scales represent zones of increased porosity and permeability. They may form networks, and therefore, are able to store and carry vast amounts of water. These groundwater systems, called fracture zone aquifers, are similar in some ways to karst systems.

The concept of fracture zone aquifers explains the behavior of groundwater in large fault-controlled watersheds. Fault zones in this case serve as collectors and transmitters of water from one or more recharge zones with surface and subsurface flow strongly controlled by regional fault patterns.

Both the yield and the quality of water in these zones are usually higher than average wells in any type of rock. High-grade water for such a region would be 250 gallons (950 liters) per minute or greater. In addition the total dissolved solids measured in the water from such high-yielding wells will be lower than the average for the region.

The quality and amount of water obtainable from fracture zone aquifers are influenced by the pattern of fractures and their related secondary porosity over an entire watershed area. It is important to understand how the fracture pattern varies across a basin to be able to determine the unique effects of secondary porosity on the processes of groundwater flow, infiltration, transmissivity, and storage, and ultimately find and use the water in the fractures.

Variations in precipitation over the catchment area can determine how a fracture zone aquifer system is recharged. One example is orographic effects where the precipitation over the mountains is substantially greater than at lower elevations. The rainfall is collected over a large catchment area, which contains zones with high permeability because of intense bedrock fracturing associated with major fault zones. The multitude of fractures within these highly permeable zones "funnel" the water into other fracture zones down gradient. These funnels may be in a network hundreds of square miles in area.

The fault and fracture zones serve as conduits for groundwater and often act as channelways for surface flow. Intersections form rectilinear drainage patterns sometimes exposed on the surface but are also represented below the surface and converge down gradient. In some regions these rectilinear patterns are not always visible on the surface due to vegetation and sediment cover. The convergence of these groundwater conduits increases the amount of water available as recharge. The increased permeability, water volume, and ratio of water to minerals within these fault/fracture zones help to maintain the quality of water supply. These channels occur in fractured, nonporous media (crystalline rocks) as well as in fractured, porous media (sandstone, limestone).

At some point in the groundwater course, after convergence, the gradient decreases. The sediment cover over the major fracture zone becomes thicker and acts as a water storage unit with primary porosity. The major fracture zone acts as both a transmitter of water along conduits and a water storage basin along connected zones with secondary (and/or primary) porosity. Groundwater within this layer or lens often flows at accelerated rates. The result can be a pressurization of groundwater both in the fracture zone and in the surrounding material. Rapid flow in the conduit may be replenished almost instantaneously from precipitation. The surrounding materials are replenished more slowly, but also release the water more slowly and serve as a storage unit to replenish the conduit between precipitation events.

Once the zones are saturated, any extra water that flows into them will overflow, if an exit is available. In a large area watershed, it is likely that this water flows along subsurface channelways under pressure until some form of exit is found in the confining environment. Substantial amounts of groundwater may flow along the main fault zone controlling the watershed and may vent at submarine extensions of the fault zone forming coastal or offshore freshwater springs.

Fracture zone aquifers are most common in areas underlain by crystalline rocks and where these rocks have undergone a multiple deformational history that includes several faulting events. It is especially applicable in areas where recharge is possible from seasonal and/or sporadic rainfall on mountainous regions adjacent to flat desert areas.

Fracture zone aquifers are distinguished from horizontal alluvial or sedimentary formation aquifers in that (1) they drain extensive areas and many extend for tens of miles (several tens of km); (2) they constitute conduits to mountainous regions where the recharge potential from rainfall is high; (3) some may connect several horizontal aquifers, and thereby increase the volume of accumulated water; (4) because the source of the water is at higher elevations, the artesian pressure at the groundwater level may be high; and (5) they are usually missed by conventional drilling because the water is often at the depth of hundreds of meters.

The characteristics of fracture zone aquifers make them an excellent source of groundwater in arid and semiarid environments. Fracture zone aquifers are being increasingly used in arid regions. Groundwater resources in arid and semiarid lands are scarce and must be properly used and thoughtfully managed. Most of these resources are "fossil," having accumulated under wet climates during the geological past. The present rates of recharge from the occasional rainfall are not enough to replenish the aquifers. Therefore the resources must be used sparingly without exceeding the optimum pumping rates for each water well field.

GROUNDWATER DISSOLUTION

Groundwater also reacts chemically with the surrounding rocks; it may deposit minerals and cement together grains, causing a reduction in porosity and permeability, or form features like stalagtites and stalagmites in caves. In other cases, particularly when acidic water moves through limestone, it can dissolve the rock, forming caves and underground tunnels. Sinkholes form where these dissolution cavities intersect the surface of the Earth.

Groundwater dissolution leads to the development of a distinctive class of landforms called karst terranes where caves can collapse, leaving sinkholes and valleys on the surfaces, and eventually evolve into spectacular towers and pinnacles of nondissolved rock surrounded by the former cave passageways. South China is famous for highly evolved karst terranes, whereas parts of the U.S. Midwest are known for well-developed underground cave systems.

GROUNDWATER CONTAMINATION

Natural groundwater is typically rich in dissolved elements and compounds derived from the soil, regolith, and bedrock through which the water has migrated. Some of these dissolved elements and compounds are poisonous, whereas others are tolerable in small concentrations but harmful in high concentrations. Human and industrial waste contamination of the groundwater is increasing, and the overuse of groundwater resources has caused groundwater levels to drop and has led to other problems, especially along coastlines. Seawater may move in to replace depleted freshwater, and the ground surface may subside when the water is removed from the pore spaces in aquifers.

The U.S. Public Health Service has established limits on the concentrations of dissolved substances (called total dissolved solids, or t.d.s.) in natural waters that are used for domestic and other purposes. The table of "Drinking Water Standards for the United States" lists these limits for the United States. Many other countries, particularly those with chronic water shortages such as many in the Middle East, have much more lenient standards. Sweet water is preferred for domestic use and has fewer than 500 milligrams (mg) of total dissolved solids per liter (L) of water. Fresh and slightly saline water, with t.d.s. of 1,000–3,000 mg/L, is suitable for use by livestock and irrigation. Water with higher concentrations of t.d.s. is unfit for humans or livestock. Irrigation of fields using waters with high concentrations of t.d.s. is also not recommended, as the water will evaporate but leave the dissolved salts and minerals behind, degrading and eventually destroying the productivity of the land.

DRINKING WATER STANDARDS FOR THE UNITED STATES

Water Classification	Total Dissolved Solids (T.D.S.)
Sweet	< 500 mg/L
Fresh	500–1,000 mg/L
Slightly saline	1,000–3,000 mg/L
Moderately saline	3,000–10,000 mg/L
Very Saline	10,000–35,000 mg/L
Brine	> 35,000 mg/L

Either a high amount of total dissolved solids or the introduction of a specific toxic element can reduce the quality of groundwater or contaminate it. Most of the total dissolved solids in groundwater are salts derived from dissolution of the local bedrock or soils derived from the bedrock. Salts can also seep into groundwater supplies from the sea along coastlines, particularly if the water is being pumped out for use. In these cases seawater often moves in to replace the depleted freshwater. This process is known as seawater intrusion, or seawater incursion.

Dissolved salts in groundwater commonly include bicarbonate (HCO_3^-) and sulfate (SO_4^{2-}) ions, often associated with other ions. Dissolved calcium (Ca^{2+}) and magnesium (Mg^+) ions can cause the water to become "hard." Hard water is defined as containing more than 120 parts per million dissolved calcium and magnesium. The dissolved ions in hard water make it difficult to lather soap, and they form a crusty mineralization buildup on faucets and pipes. Adding sodium (Na^+) in a water softener can soften hard water, but people with heart problems or those who are on a low-salt diet should not do this. Hard water is common in areas where the groundwater has moved through limestone or dolostone rocks, which contain high concentrations of Ca^{2+} and Mg^{2+}–rich rocks that groundwater easily dissolves.

Groundwater may have many other contaminants, some natural and others the result of human activity. Human pollutants including animal and human waste, pesticides, industrial solvents, road salts, petroleum products, and other chemicals are a serious problem in many areas. Some of the biggest and most dangerous sources of groundwater contamination include chemical and gasoline storage tanks, septic systems, landfills, hazardous waste sites, military bases, and the general widespread use of road salt and chemicals such as fertilizers or pesticides.

The Environmental Protection Agency has led the cleanup from spills from leaking chemical storage tanks in the United States. There are estimated to be more than 10 million buried chemical storage tanks in the United States, containing chemicals such as gasoline, oil, and hazardous chemicals. These tanks can leak over time, and many of the older ones have needed to be replaced in the past two decades, bringing in a new generation of tanks that should last longer and corrode less.

Home and commercial septic systems pose serious threats to some groundwater systems. Most are designed to work effectively and harmlessly, but some were not installed properly or were poorly designed.

In many cases groundwater supplies have been contaminated by chemicals and other contaminants that were poured down drains, entering the septic system and then the groundwater system.

There are more than 20,000 known and abandoned hazardous waste sites in the United States. Some of these contain many barrels of chemicals and hazardous materials that can and do leak, contaminating the water supply. Landfills may also contain many hazardous chemicals—when landfills are designed they are supposed to incorporate a protective impermeable bottom layer to prevent chemicals from entering the groundwater system. But some chemicals that are erroneously placed in the landfill sometimes burn holes in the basal layer, making their way (with a myriad of other chemicals) into the groundwater system.

In parts of the country that freeze, road salts are commonly used to reduce the amount of ice on the roads. These salts dissolve in rainwater and can eventually make their way down into the aquifers as well, turning an aquifer salty. Together with chemicals from lawn and farm field fertilization and application of pesticides, the amount of these chemicals starts to become significant for the safety of the water quality below ground.

Groundwater contamination, whether natural or human-induced, is a serious problem because of the importance of the limited water supply. Pollutants in the groundwater system do not simply wash away with the next rain, as many dissolved toxins in the surface water system do. Groundwater pollutants typically have a residence time, or average length of time that it remains in the system, of hundreds or thousands of years. Many groundwater systems are capable of cleaning themselves from natural biological contaminants using bacteria, but other chemical contaminants have longer residence times.

Arsenic in Groundwater

In parts of the world many people have become sick from arsenic dissolved in the groundwater. Arsenic poisoning leads to a variety of horrific diseases, including hyperpigmentation (abundance of red freckles), hyperkeratosis (scaly lesions on the skin), cancerous lesions on the skin, and squamous cell carcinoma. Arsenic may be introduced into the food chain and body in several ways. In Guizhou Province, China, villagers dry their chili peppers indoors over coal fires. Unfortunately, the coal is rich in arsenic (containing up to 35,000 parts per million arsenic), and much of this arsenic is transferred to the chili peppers during the drying process. Thousands of the local villagers now suffer arsenic poisoning, with cancers and other forms of the disease ruining families and entire villages.

Most naturally occurring arsenic is introduced into the food chain through drinking contaminated groundwater. Arsenic in groundwater is commonly formed by the dissolution of minerals from weathered rocks and soils. In Bangladesh and West Bengal, India, 25–75 million people are at risk for arsenosis, because of high concentrations of natural arsenic on groundwater.

Since 1975 the maximum allowable level of arsenic in drinking water in the United States has been 50 parts per billion. The EPA has been considering adopting new standards on the allowable levels of arsenic in drinking water. Scientists from the National Academy recommend that the allowable levels of arsenic be lowered to 10 parts per billion, but this level was overruled by the Bush administration. The issue is cost: the EPA estimates that it would cost businesses and taxpayers $181 million per year to bring arsenic levels to the proposed 10 parts per billion level, although some private foundations suggest that this estimate is too low by a factor of three. They estimate that the cost would be passed on to the consumer, and residential water bills would quadruple. The EPA estimates that the health benefits from such a lowering of arsenic levels would prevent between 7 and 33 deaths from arsenic-related bladder and lung cancer per year. These issues reflect a delicate and difficult choice for the government. The EPA tries to "maximize health reduction benefits at a cost that is justified by the benefits." How much should be spent to save 7–33 lives per year? Would the money be better spent elsewhere?

Arsenic is not concentrated evenly in the groundwater system of the United States, or anywhere else in the world. The U.S. Geological Survey issued a series of maps in 2000 showing the concentration of arsenic in tens of thousands of groundwater wells in the United States. Arsenic is concentrated mostly in the Southwest, with a few peaks elsewhere such as southern Texas, parts of Montana (due to mining operations), and parts of the upper plains states. Perhaps a remediation plan that attacks the highest concentrations of arsenic would be the most cost-effective and have the highest health benefit.

Contamination by Sewage

A major problem in groundwater contamination is sewage. If chloroform bacteria get into the groundwater, the aquifer is ruined, and care must be taken and samples analyzed before water is used for drinking. In many cases sand filtering can remove bacteria, and aquifers contaminated by chloroform bacteria and other human waste can be cleaned more easily than aquifers contaminated by many other elemental and mineral toxins.

Although serious, detailed discussion of groundwater contamination by human waste is beyond the scope of this encyclopedia, the reader is referred to the sources listed at the end of the chapter for more detailed accounts.

Seawater Intrusion in Coastal Aquifers

Encroachment of seawater into drinking and irrigation wells is an increasing problem for many coastal communities around the world. Porous soils and rocks beneath the groundwater table in terrestrial environments are generally saturated with fresh water, whereas porous sediment and rock beneath the oceans is saturated with salt water. In coastal environments there must be a boundary between the fresh groundwater and the salty groundwater. In some cases this is a vertical boundary, whereas in other cases the boundary is inclined with the denser salt water lying beneath the lighter fresh water. In areas where there is complex or layered stratigraphy, the boundary may be complex, consisting of many lenses.

In normal equilibrium situations the boundary between the fresh and salty water remains rather stationary. In times of drought the boundary may move landward or upward, and in times of excessive precipitation the boundary may move seaward and downward. As sea levels rise the boundary moves inland and wells that formerly tapped fresh water begin to tap salt water. This is called sea water intrusion or encroachment.

Many coastal communities have been highly developed, with many residential neighborhoods, cities, and agricultural users obtaining their water from groundwater wells. When these wells pump more water out of coastal aquifers than is replenished by new rainfall and other inputs to the aquifer, the fresh water lens resting over the salt water lens is depleted. This also causes the salt water to move in to the empty pore spaces to take the place of the fresh water. Eventually as pumping continues the fresh water lens becomes so depleted that the wells begin to draw salt water out of the aquifer, and the well becomes effectively useless. This is another way that salt water intrusion or encroachment can poison groundwater wells. In cases of severe drought the process may be natural, but in most cases seawater intrusion in caused by over-pumping of coastal aquifers, aided by drought conditions.

Many places in the United States have suffered from seawater intrusion. For instance, many East Coast communities have lost use of their wells and had to convert to water piped in from distant reservoirs for domestic use. In a more complicated scenario western Long Island of New York experienced severe seawater intrusion into its coastal aquifers because of intense overpumping of its aquifers in the late 1800s and early 1900s. Used water that was once returned to the aquifer by septic systems began to be dumped directly into the sea when sewers were installed in the 1950s, with the result that the water table dropped more than 20 feet over a period of 20 years. This drop was accompanied by additional seawater intrusion. The water table began to recover in the 1970s when much of the area converted to using water pumped in from reservoirs in the Catskill Mountains to the north of New York City.

SUMMARY

Most of the world's freshwater is locked in glaciers or ice caps, and about 25 percent of the freshwater is stored in the groundwater system. Water in the groundwater system is constantly but slowly moving, being recharged by rain and snow that infiltrates the system, and discharging in streams, lakes, springs, and extracted from wells. Water that moves through a porous network forms aquifers, and underground layers that restrict flow are known as aquicludes. Fracture zone aquifers comprise generally nonpermeable, nonporous crystalline rock units, but faults and fractures that cut the rock create new or secondary porosity along the fractures. If exposed to the surface, these fractures may become filled with water and serve as excellent sources of water in dry regions.

The groundwater system is threatened by pollutants that range from naturally dissolved but deadly elements such as arsenic, to sewerage, to industrial wastes and petroleum products that have leaked from underground storage containers, or were carelessly dumped. Some chemical elements have a short residence time in the groundwater system and are effectively cleaned before long, but other elements may last years or thousands of years before the groundwater is drinkable again.

See also HYDROSPHERE; METEORIC; SOILS.

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Halley, Edmond (1656–1742) British *Astronomer, Geophysicist, Mathematician, Meteorologist, Physicist* Edmond Halley was born on November 8, 1656, in Shoreditch, England, and is best known for the comet bearing his name, Halley's Comet. Halley married Mary Tooke in 1682, and the couple had three children. He died on January 14, 1742.

Edmond Halley studied mathematics at an early age while at St. Paul's School in London, before moving to the Queen's College at Oxford in 1673. During his undergraduate years at Oxford, Halley published several scientific papers on sunspots and the solar system.

After graduating from Oxford Halley visited the South Atlantic Ocean island of St. Helena to examine the southern stars, then returned to England in 1678, publishing his observations of the southern sky as his *Catalogus Stellarum Australium* in 1679. This work led to his being awarded a master of arts degree from Oxford and his election as a fellow of the Royal Society.

Some eight years after his voyage to the South Atlantic Halley published the second volume from his field observations, this one on the southern trade winds and monsoons, and his deduction that atmospheric motions were ultimately driven by solar heating of the atmosphere. Halley became interested in gravity and studied 16th century Austrian mathematician Kepler's laws of planetary motion and met with Sir Isaac Newton on the matter in 1684. He found that Newton had derived proof of Kepler's laws. Halley convinced Newton to publish his works and even paid the cost of printing.

In 1691 Halley applied for the position of Savilian Professor of Astronomy at Oxford, but since his views on religion were atheistic, the archbishop of Canterbury opposed his appointment and gave it instead to David Gregory, who was supported by Newton.

After working to develop actuarial models for the British government, Halley returned to science and was given command of a vessel to sail to the South Atlantic to study variations in the magnetic compass. After an initial voyage was terminated because of insubordination by the crew in 1698, he sailed from September 1699 to September 1700, then in 1701 published his observations of the magnetic field as his *General Chart of the Variation of the Compass*, the first chart ever to show magnetic isogonic lines, contour lines that show places of constant magnetic declination.

After his detractors at Oxford died, Halley was appointed Savilian Professor of Geometry in 1703 and was given an honorary doctor of law in 1710. While he was in the Savilian Professorship, Halley pursued historical astronomy and published his analysis of past accounts of comet sightings as *Synopsis Astronomia Cometicae* in 1705. He noted comet sightings from the years 1456, 1531, 1607; 1682, and noting the 75–76 year repeat cycle of the comets, he suggested that these sightings were of the same comet, and that it would return in 1758. When the comet did return, it became known as Halley's comet.

See also ASTRONOMY; COMET; SUN.

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Cook, Alan H. *Edmond Halley: Charting the Heavens and the Seas*. Oxford: Clarendon Press, 1998.

Hess, Harry (1906–1969) American *Geologist* Harry Hammond Hess is best known for formulating a theory on the origin and evolution of ocean basins. Drawing on observations from which Alfred Wegener proposed his theory of continental drift in 1912, Hess visualized a process occurring deep below the oceanic crust that caused seafloor spreading. In this model the seafloor is created at ridges and sinks at trenches back into the Earth's mantle. This concept provided a model that catapulted the plate tectonics theory into the earth sciences mainstream.

EARLY YEARS

Harry Hammond Hess was born on May 24, 1906, in New York City, to Julian and Elizabeth Engel Hess. His father worked at the New York Stock Exchange. Harry had one brother, Frank. When he was five Harry's parents photographed him in a sailor suit and fittingly titled the portrait "The Little Admiral," foreshadowing Harry's career. He attended Asbury Park High School in New Jersey, where he specialized in foreign languages.

In 1923 Hess enrolled at Yale University, where he planned to major in electrical engineering. He changed his major to geology and received a bachelor's degree in 1927. The Loangwa Concessions, Ltd. mining company hired Hess to perform exploratory geological mapping and to look for mineral deposits in Zimbabwe (then Rhodesia), in southern Africa. He did not enjoy this work because he had to survey where he was told rather than where he believed he would find something valuable. After two years, he returned to the United States to attend graduate school, but this experience had taught him to appreciate the importance of fieldwork in geological research.

As a doctoral candidate at Princeton University he learned about mineralogy (the study of minerals, their identification, distribution, and properties), petrology (the study of the origin, composition, and structure of rocks), and the structure of the ocean basin. In 1931 he accompanied the Dutch geophysicist Felix A. Vening-Meinesz on a mission to carry out gravity measurements in the West Indies and the Bahamas. Information about gravity at different positions over the Earth's surface gives geologists insight into the composition of the rock under the surface because gravitational fields are stronger over areas with greater mass, which are denser. The measurements had to be performed within a submarine because a pendulum system was used, and ships moved around too much from the surface waves and wind. One interesting observation from this voyage was that the gravity over the Caribbean trench was much weaker than expected. A trench is a long, narrow furrow along the edges of the ocean floor; thus the gravity was expected to be weaker, as it is over all valleys, but the extreme weakness told Hess and Vening-Meinesz that the underlying structure was unusual. Scientists were aware that volcanoes were often located adjacent to trenches and that earthquakes occurred nearby. Hess wondered about the implications of this finding.

Hess obtained a Ph.D. in geology in 1932. His dissertation was on the serpentinization of a large peridotite intrusive located in the Blue Ridge Mountains of Virginia. A peridotite is a type of igneous rock containing the minerals olivine and pyroxene, and intrusive means that the rock formed as magma without reaching the surface of the Earth. Serpentinization of peridotites is a chemical process by which the minerals olivine and pyroxene change to the mineral serpentine. The peridotite rock is changed into serpentinite, a rock composed of the mineral serpentine. Hess remained interested in mineralogy throughout his career and published two papers, "Pyroxenes of Common Mafic Magmas" (1941) and "Stillwater Igneous Complex, Montana" (1960), that both became classics in the field. NASA later named Hess the principal investigator for pyroxene studies of moon rock samples.

After receiving a doctorate Hess taught at Rutgers University in New Jersey from 1932 to 1933, then worked as a research associate at the Geophysical Laboratory of the Carnegie Institution of Washington, D.C., for one year. He obtained a teaching position in geology at Princeton University in 1934 and remained associated with Princeton until 1966. That same year he married Annette Burns, and they eventually had two sons, George and Frank.

FROM THE ATLANTIC TO THE PACIFIC

Hess had joined the U.S. Navy as a lieutenant to facilitate operations on a navy submarine that he used for gravity studies following his research with Vening-Meinesz. He was in the naval reserves when Japan attacked Pearl Harbor on December 7, 1941. Hess reported for active duty the next morning. Because he had submarine experience, he became an antisubmarine warfare officer with responsibility for detecting enemy submarine operations patterns in the North Atlantic. Hess advised the U.S. Navy that German submarines might be using the cloud cover north of the Gulf Stream (a current that runs from the Gulf of Mexico up the U.S. Atlantic coastline) to escape detection during surfacing. This suggestion resulted in the clearing out of submarines in the North Atlantic within two years. Hess arranged a transfer to the decoy vessel USS *Big Horn* to test the effectiveness of the submarine detection program; he then remained on sea duty for the rest of the war. As commanding officer of the transport vessel USS *Cape Johnson,* Hess carefully chose his travel routes to Pacific Ocean landings on the Marianas, Philippines, and Iwo Jima, continuously performing scientific surveying and profiling of the ocean floor across the North Pacific Ocean.

Hess took advantage of his time in the navy by patterning the travel routes to facilitate his studies on the geology of the ocean floor. He installed a deep-sea echo sounder on his transport ship and used it continuously. This equipment measured the depth of the sea bottom over which the ship traveled by sending a sound signal downward from the ship and measuring the time it took for the signal to bounce back from the ocean floor. Using these data Hess constructed bathymetric maps that showed the contours of the ocean floor across a large area of the Pacific. While collecting bathymetric data, Hess discovered flat-topped underwater volcanoes that he named *guyots* after Swiss geologist Arnold Guyot, who had founded the department of geology at Princeton University in 1854, and Princeton named the geology building after him. Hess remained in the naval reserves until his death, attaining the rank of rear admiral in 1961.

BAFFLING MARINE GEOLOGY DISCOVERIES

In July 1950 a group of scientists studying the seafloor of the Pacific Ocean made surprising discoveries that influenced the formulation of Hess's developing ideas about the origin and evolution of ocean basins. Scientists believed that the oceanic crust was mostly flat and extremely thick owing to the accumulation of billions of years of sediment from continental erosion. Using explosives and seismic waves, the crew determined the thickness of the oceanic crust to be about four miles (7 km). This was much thinner than expected, since the continental crust was known to be about five times thicker. Geologists thought the oceans had existed for 4 billion years, so why was there so little accumulated sediment? The crew took samples from guyots and was surprised to find coral rather than rocky sand, as anticipated. Coral is usually found in shallow areas, and some guyots are two miles (3.2 km) underwater. It also proved to be approximately 130 million years old, hundreds of millions of years younger than expected. Fossil evidence further confirmed the relatively young age of the ocean floor.

A few years later American oceanographer Maurice Ewing observed that oceanic ridges, underground mountain ranges, have rifts, or valleys, running through their centers. The seam of the rift appeared to be due to splitting apart, which was interesting because, in contrast, terrestrial mountain ranges were believed to arise from compression, from chunks of land being forced together. The presence of lava and absence of sediment along the ridges also baffled scientists.

PROPOSAL OF SEAFLOOR SPREADING

Hess contemplated these many unexpected discoveries in relation to the theory of continental drift proposed by the German meteorologist and geophysicist Alfred Wegener in 1912. After noticing that the east coast of South America and the west coast of Africa fit together like pieces of a jigsaw puzzle and collecting additional fossil evidence, Wegener concluded that the continents had once been connected, but split and drifted thousands of miles apart. Wegener offered no explanation for the mechanism driving continental drift, but Hess modified Wegener's theory and provided a plausible driving force. Wegener thought that drifting continents somehow plowed through the ocean floor, but Hess believed they rode along passively as the ocean floor was carried away from its ridges.

In 1960 Hess first proposed his theory of seafloor spreading. In doing so he explained the midoceanic ridge splitting, the presence of lava surrounding ridges, and the thinness of the oceanic crust. The attractive model suggested that the oceanic crust was indeed splitting at a seam, the rift in the center of the midoceanic ridge. As it split, melted magma rose through these weak areas and erupted as lava from the spreading ridges, forming new crust composed mostly of basalt as it cooled. The newly formed crust then was carried away by the mantle spreading out laterally beneath the crust, away from the ridge where it would eventually dive back beneath the surface of the Earth at trenches, located along faults formed by compression. At the trenches slabs of crust would be forced under other slabs of crust, back into the Earth's mantle.

Hess proposed convection, heat transfer by fluid motion, as the driving force behind the process of seafloor spreading. The mantle, located just underneath the crust, is solid rock formed mostly from iron and magnesium minerals, but just below the surface it may melt into magma, which cools into the igneous rock basalt. Though solid, the molten mantle can flow slowly like a fluid, forming convection cells. The hotter rock is less dense and rises, and as the rock cools, it sinks. When it cools and sinks, it pulls the overlying crust down into the mantle with it. The crust that disappeared into the trenches was constantly replenished by newly erupted lava at the ridge. Hess called this paper "an essay in geopoetry" and issued preprints of it in 1960. The official paper, "History of Ocean Basins," was published in 1962 by the Geological Society of America in a symposium volume called *Petrologic Studies: A Volume in Honor of A. F. Buddington*. Buddington had been Hess's petrology professor at Princeton and became a close friend.

Hess's paper was well received, and additional paleomagnetic evidence supporting his theory of seafloor spreading soon came out. Paleomagnetism is the science of reconstruction of the Earth's ancient magnetic field and the positions of the continents from the evidence of magnetization in ancient rocks. Because the Earth acts like a giant spherical magnet, rocks containing iron-rich minerals are magnetized in alignment with the Earth's poles. When magnetic rocks solidify, they become a permanent indicator of the direction of the Earth's magnetic field at the time of their solidification. Every few million years the Earth's poles reverse, thus the age of the rocks and their direction of magnetization provide geophysicists with information regarding the history of the direction of the Earth's magnetic poles.

In 1963 two young British geologists, Fred J. Vine and Drummond H. Matthews, and Lawrence Morley of the Canadian Geological Survey independently described magnetic anomalies that lent further evidence in support of seafloor spreading. Stripes parallel to the mid-oceanic ridge extended laterally from it, with reversals in the magnetic direction every several hundred kilometers. Vine thought that when the magma that erupted from the rift in the ridge cooled, it magnetized in the direction of the current magnetic field, then was carried away laterally from the ridge. Hess wholeheartedly accepted this hypothesis. Further studies performed in 1966 on the magnetic stripes showed that the patterns were indeed parallel to the ridges, and they were bilaterally symmetrical in magnetics and age. This evidence, along with evidence showing the seafloor was older the farther away it was from the ridges, confirmed the lateral movement of the crust and further established Hess's theory of seafloor spreading, as did future evidence of fossils and underwater core samples.

ADMIRED AND HONORED

Beginning in 1962 Hess chaired the Space Science Advisory Board of the National Academy of Sciences. The board's responsibility was to advise NASA. In 1966 he was at Woods Hole, Massachusetts, chairing a meeting to discuss the scientific objectives of lunar exploration when he began having chest pains. He died of a heart attack on August 25, 1969, and was buried at the Arlington National Cemetery.

Hess was elected to membership of several academic societies including the National Academy of Sciences (1952), the American Philosophical Society (1960), and the American Academy of Arts and Sciences (1968). He served as president of the Geodesy Section (1951–53) and the Tectonophysics Section (1956–58) of the American Geophysical Union, the Mineralogical Society of America (1955), and the Geological Society of America (1963). Because he was well respected as a scientist, he also was appointed chairman of the Committee for Disposal of Radioactive Wastes, chairman of the Earth Sciences Division of the National Research Council, and chairman of the Space Science Advisory Board of the National Academy of Sciences. Along with oceanographer Walter Munk, he was a principal player in the Mohole Project, the goal of which was to drill beneath the oceanic crust into the mantle. The Geological Society of America awarded Hess the Penrose Medal for distinguished achievement in the geological sciences in 1966, and NASA awarded Hess a Distinguished Public Service Award posthumously. Because of his outstanding achievements the American Geophysical Union created the Harry H. Hess Medal for outstanding achievements in research in the constitution and evolution of the Earth and sister planets.

Hess's friends have described his personality as puckish and courageous. Part of Hess's greatness as a scientist was his willingness to entertain new ideas, even if they conflicted with his own previous conclusions. After all, sometimes wrong ideas ushered in new eras of scientific accomplishment. In suggesting that the ocean basins were continuously recycled, Hess explained why seafloor spreading did not cause Earth to grow, why the layer of sediment on the ocean floor was thinner than expected, and why oceanic rocks are younger than continental rocks. Hess's model of seafloor spreading has become part of the foundation knowledge of the geological sciences and has evolved into the theory of plate tectonics. Many questions regarding the forces that occur deep within the Earth are still being actively investigated today.

See also CONVERGENT PLATE MARGIN PROCESSES; DIVERGENT PLATE MARGIN PROCESSES; PLATE TECTONICS; WEGENER, ALFRED.

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Hipparchus **(160–120 B.C.E.) Greek *Astronomer, Geographer, Mathematician*** Hipparchus was one of the greatest astronomical observers of ancient Greece. He is best known for his accurate quantitative models for the motion of the Sun and Moon. He used a trigonometric table and techniques from the Chaldeans (a Semitic people from Mesopotamia) to derive the sizes of Sun and Moon, to determine the latitude and longitude of places on the Earth, and to predict solar eclipses. He is credited also with compilation of the first star catalog and invention of the astrolabe.

Hipparchus was born in Nicaea in the ancient Greek district of Bithynia (now Iznik, Turkey). Historical accounts of his life from Ptolemy and Pliny the Elder suggest that he was born in 190 B.C.E., and it is known from his writings that he visited Alexandria, Egypt, and Babylon, but the dates of these trips are not known. Hipparchus is thought to have spent the later years of his life, and to have died in about 120 B.C.E., on the Greek island of Rhodes in the Aegean Sea.

Much of Hipparchus's scientific work has been lost to antiquity, and most is known from writings by scientists from more recent times, especially Ptolemy. From these writings it is known that Hipparcus wrote at least 14 books and published a star catalog later incorporated into Ptolemy's star catalog.

The world's first known trigonometric table is that of Hipparchus, who used the tables to calculate the eccentricity and orbits of the Sun and Moon. He was also concerned with calculating the distances to the Sun and Moon, and the sizes of these objects. He wrote about his trigonometric methods in the book *Toon en kuklooi eutheioon* (Of lines inside a circle), which has been lost to civilization. Hipparchus worked on stereographic projections (a mapping function that projects a sphere onto a plane), showing that the projections can be made to preserve angles so that they are the same on the projection as in the physical world, and that circles on the sphere that do not pass through the center of the sphere project as circles on the projection (i.e., they are not great circles). Hipparchus used these principles to develop the astrolabe, a historical astronomical instrument used to locate the positions of the Sun, Moon, stars, and planets. Astrolabes also proved useful in calculating location and time for ships at sea, and for navigation.

One of the topics of great interest to Hipparchus was the motion of the Moon. He calculated accurately the Moon's period and predicted eclipses with great accuracy. He was also concerned with the length of the year and the apparent motion of the Sun, and observed the summer solstice in 135 B.C.E., as well as many solar equinoxes. He used these measurements to calculate the length of the year. Toward the end of his career Hipparchus wrote a book on his solar observations and calculations, *Peri eniausíou megéthous* (On the length of the year). In this book he concluded that the year lasted 365 1/4–365 1/300 days.

Hipparchus worked to determine the size of the Sun and the Moon, and the distance to these objects, publishing his work in two books, *Peri megethoon kai 'apostèmátoon* (On sizes and distances). Although his books do not survive, later accounts suggest that he calculated the Sun to be 2,550 Earth radii and the mean distance to the Moon to be 60.5 Earth radii.

Hipparchus may be most famous for his discovery of the precession of the equinoxes through his observations of the Sun and Moon. He published books on precession titled *On the Displacement of the Solsticial and Equinoctial Points* and *On the Length of the Year,* and Ptolemy and others later used these works in their celestial observations and catalogs.

See also ASTRONOMY; SOLAR SYSTEM; SUN.

historical geology Historical geology is the science that uses the principles of geology to reconstruct and interpret the history of the Earth. It includes study of the changes in the Earth's surface, the record of life, stratigraphy, dating of different geologic units, the history of the motions of plates and past positions of continents, the formation of mountain belts, basins, and past climates. The Earth can be like a jigsaw puzzle, and historical geology attempts to understand the causes and sequence of events that led to the observable features in the geological record, including the origin and destiny of living things and establishing the chronology of events in Earth history by examining the rock record. Geologists who have studied the history of Earth have gradually come to realize that the planet is very old and has had a complex history. The rock record shows that the life-forms on the planet have evolved from preexisting species by means of slow, gradual changes over long periods of time, and this evolution has been punctuated by several major episodes of mass extinctions, where large numbers of species and individual organisms within species have suddenly died off, to be replaced by totally new species in the next layer of younger strata.

STRATIGRAPHIC PRINCIPLES AND THE ROCK RECORD AS INDICATORS OF EARTH HISTORY

Stratigraphy is the study of rock strata or layers and is concerned with aspects of the rock layers such as their succession, age relationships, lithologic composition, geometry, distribution, correlation, fossil content, and environments of deposition. The main aim of stratigraphy is to understand and interpret the rock record in terms of paleoenvironments, mode of origin of the rocks, and the causes of similarities and differences between different stratigraphic units. These units can then be compared across regions, continents, and oceans to obtain an understanding of the conditions on Earth at the time the rocks were deposited.

The most basic unit of stratigraphy is the formation, a distinctive series of strata that originated through the same formative processes. Formations must be distinctive in appearance and easily recognizable. They can be recognized on the basis of lithology, which consists of the composition of the mineral grains, color, texture of grains, thickness and geometry of stratification, character of organic remains (fossils), and outcrop character. According to the code of stratigraphy, there is a hierarchy of naming different layers in rocks. A single layer is called a stratum, and the many layers within a formation are called strata. Groups consist of several related formations, whereas systems of strata consist of several groups of strata.

Early stratigraphers tended to regard Earth history and the stratigraphic record in a simplistic way. Most believed that the stratigraphic divisions being named in Europe were present and of the same age worldwide, developing a model of the Earth that was like a layered cake, with uniform stratigraphic layers around the globe. Gradually it became recognized that there may be some lateral variations between formations. For instance, in 1789 the French polymath, chemist, geologist, farmer, and engineer Antoine Lavoisier (1743–1794) suggested that similarities of fossils in similar sedimentary rocks might reflect environmental factors more than age. Lavoisier showed that shallow, near-shore marine sediments are coarser and contain organisms adapted to rough water, whereas deeper marine, quiet-water sediments are finer and contain delicate bottom-dwelling organisms, as well as floaters and swimmers. Lavoisier showed that different sedimentary products may form in different environments and have different groups of fossils, even though they formed at the same time. Five years later Lavoisier was beheaded during the French revolution, since he was one of 28 tax collectors and branded a traitor.

In the 1830s the British geologists Adam Sedgwick (1785–1873) and Sir Roderick Impey Murchison (1792–1871) also found that in Britain, the nonmarine Old Red Sandstone was laterally equivalent, in part, with marine sandstones. These two famous geologists found that the marine and nonmarine sandstones had an interfingering relationship, meaning one sediment type or formation grades laterally into another.

DEPOSITIONAL ENVIRONMENTS AND FACIES AS A RECORD OF HISTORICAL GEOLOGIC CONDITIONS

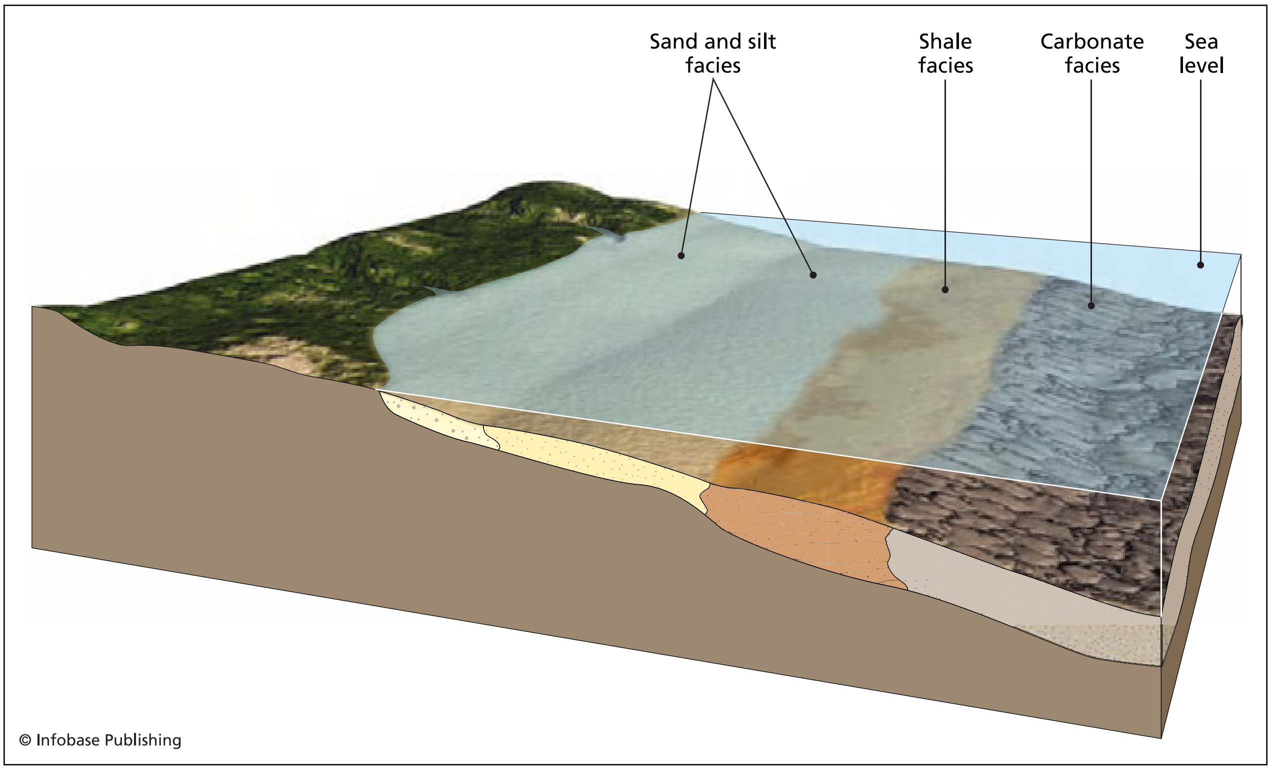
The importance of the lateral variations in strata was not appreciated until 1838 when interfingering of two different lithologies with different fossil assemblages was described from a mountainside in Switzerland. The term *sedimentary facies* described the difference in lithology between the two interfingering rock units, and the two were interpreted as products of different environments of deposition, with the gradual change in the character of the rocks reflecting a gradual change in the aspects of the original environments, such as a transition from a sandy beach to a muddy offshore shelf. It is customary to name the facies of a rock unit by the dominant lithology of the unit, for instance, a mud-rich rock might be called a muddy facies.

The analysis of sedimentary facies is aimed primarily at interpreting the environment of deposition of the rocks, and therefore includes descriptions of both rock lithologies and the fossils contained in the rocks. An important aspect of the analysis and interpretation of sedimentary facies is using the principal of uniformitarianism, where features in old rocks are compared with modern environments to understand the origin of the old features.

Facies patterns are best understood by examining changes on regional scales, and can be very useful if not essential for reconstructing past environments. By examining many different facies patterns and determining the paleoenvironments, it is possible to understand the history of environments and life on Earth, one of the goals of historical geology.

Analysis of sedimentary facies shows that sea level is constantly moving up and down, and that the land surface is also moving up and down relative to sea level. Sinking of the land relative to sea level is called subsidence, whereas uplift refers to land rising relative to sea level. Some places in the world are currently subsiding, such as Venice, Italy; New Orleans, Louisiana; and the North Sea coast of Holland. The North Sea coast has been sinking for the past 10,000 years, since the last glacial advance, such that more and more ancient shorelines are located farther and farther offshore. Likewise, the coastal environment along the Mississippi Delta of southern Louisiana is rapidly subsiding, such that many square miles of land sink below sea level every year, and the shoreline is gradually moving inland toward the city of New Orleans. As this process of subsidence continues, the sedimentary environments of the shoreline, the shallow marine and deeper marine all move landward, with the deeper facies migrating on top of the shallow ones. This pattern is produced in what is known as a marine transgression, and can be caused by the land sinking relative to the sea, or by a global sea-level rise.

In contrast to a transgression, a regression of the sea occurs when sea level falls relative to the land, and the shoreline moves away from the present-



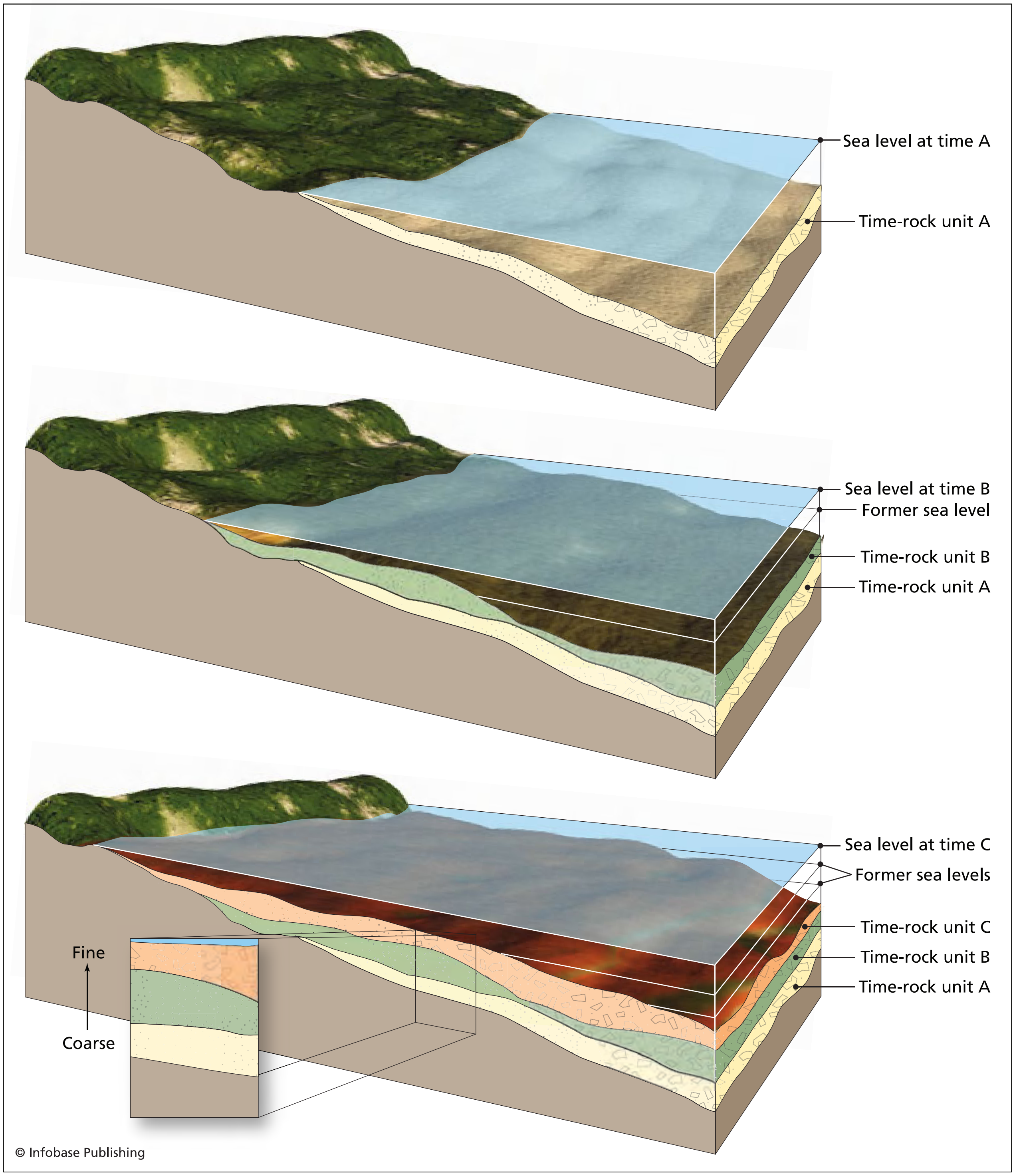
Cross section of beach and near-shore environment showing sedimentary facies change from subaerial dunes to beach to shallow marine to transitional to deep marine. Note how the rocks deposited in each facies interfinger with each other.

day coast. Like a transgression, a regression causes a continuous and gradual shift of the sedimentary environments, as well as the sedimentary and biologic products that form a wedge of material that overlies older deposits from the facies that previously existed in that location. In both transgressions and regressions the facies boundaries (and lithology changes in the rock record) form inclined surfaces, whereas time lines, corresponding to the seafloor surface at any time, may be subhorizontal surfaces, and cut across the lithologies as the paleoenvironments changed from beach to nearshore to offshore. Thus even though formations may be defined with attributes such as "near-shore sand" or "offshore mud," time lines cut across formation boundaries.

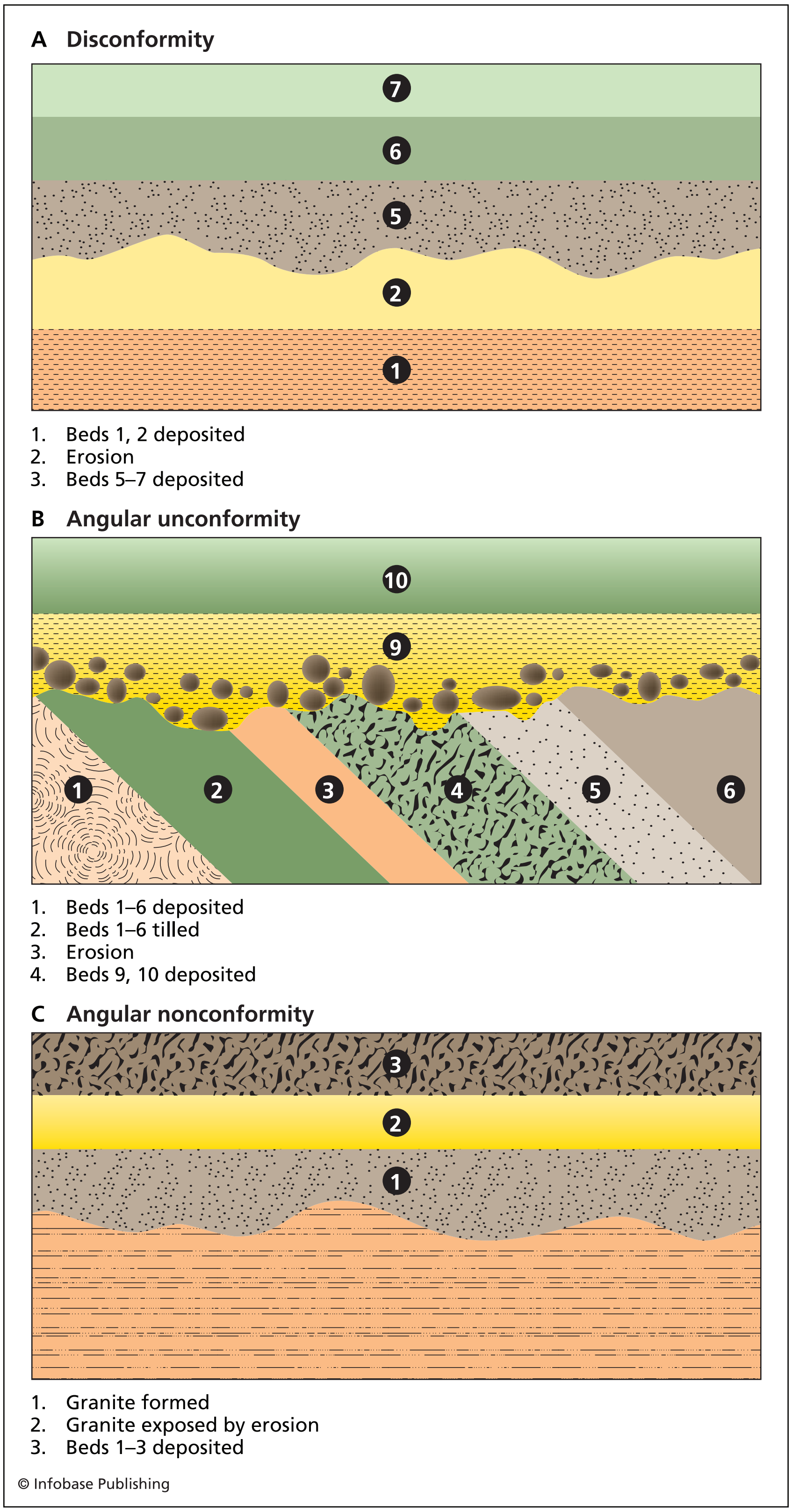
To interpret the history of an area one must often pick out characteristics of facies patterns to determine whether the sea level was rising in a transgression during deposition, or whether it was falling in a regression. Transgressive patterns are characterized by shrinking land areas, and typically transgressive rock packages are underlain by unconformity surfaces. They show a landward shift of facies through time, and become finer upward at any given location. In contrast regressive patterns that form from the uplift of the land or the fall of the sea show an enlargement of the land area, typically have an erosional unconformity at their top, show a seaward shift of facies with time, and are coarser upward at any given location.

Patterns of facies were studied extensively in the late 1800s by the German geologist Johannes Walther, who noted that facies tend to shift with time in the geological record, and that as the facies shift, adjacent environments succeed each other in the vertical sequence. This understanding led to the formation of "Walther's law," which states that the vertical progression of facies is the same as the corresponding lateral facies changes.

Understanding the local patterns of marine transgressions and regressions was a major accomplishment for geologists, but the next step, correlating the patterns from one shoreline or continent to establish a global pattern, was more difficult. In some cases it seemed as if one continent was rising or falling while others were not, and in other cases the geologic evidence suggested that sea levels were rising or falling at the same time in most locations across the world. These global sea-level rise or fall events are referred to as eustatic changes and may be caused by changes in the amount of water in the oceans from melting or freezing glaciers, or changes in the volume of the deep ocean basins by changing the volume of the midocean ridges through increased or decreased seafloor spreading. Continental collisions can also uplift large portions of the continents, effectively decreasing the amount of continental material in the oceans, expanding the volume of the ocean basins,



Rising sea level causes the sedimentary facies to migrate shoreward and be deposited one on top of the other and move progressively shoreward. A regression shows the opposite direction of migration of facies. Note how a vertical profile through these sections would yield a sequence of facies that is the same as the horizontal sequence of facies on the surface and that the order of succession can be used to tell the difference between a regressive and a transgressive sequence.



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Three types of unconformities, including disconformity, angular unconformity, and nonconformity

and causing global sea levels to fall. To determine whether sea-level changes are local or global, a well-correlated geological timescale is needed for each continent, which, over time, has led to the establishment of global eustatic sea-level curves showing the heights of sea level with time.

BIOSTRATIGRAPHY AND RELATIVE AGES OF STRATA

Biostratigraphy is the branch of stratigraphy that uses fossil assemblages and index fossils to correlate and assign relative ages to strata. Index fossils are used to identify and define geological periods, or faunal stages. Ideal index fossils are short-lived, have a broad distribution, and are easy to identify. Most good index fossils are floating or swimming organisms that live independently of the bottom environment. Many have floating larval stages that are dispersed by currents, seeds or spores blown by the wind, and that evolve rapidly. In contrast, some organisms are restricted to certain sedimentary facies and as such can indicate the paleoenvironment but not necessarily the age of the strata. A fossil zone is an interval of strata characterized by a distinctive index fossil, or fossil assemblage. These index fossils and fossil zones have the same age on a global scale and allow geologists to correlate strata from continent to continent, and to piece together a picture of the globe at any interval in the history of the Earth.

The distribution of and changes in the fossil record is controlled both by the evolution and the extinction of index fossils, and by changing environmental conditions or facies, which may cause individual organisms to migrate to a new habitat. Environmental changes are usually short-term compared with extinctions, and the two effects are easily distinguished. Fossil zones do not necessarily correspond to formation boundaries.

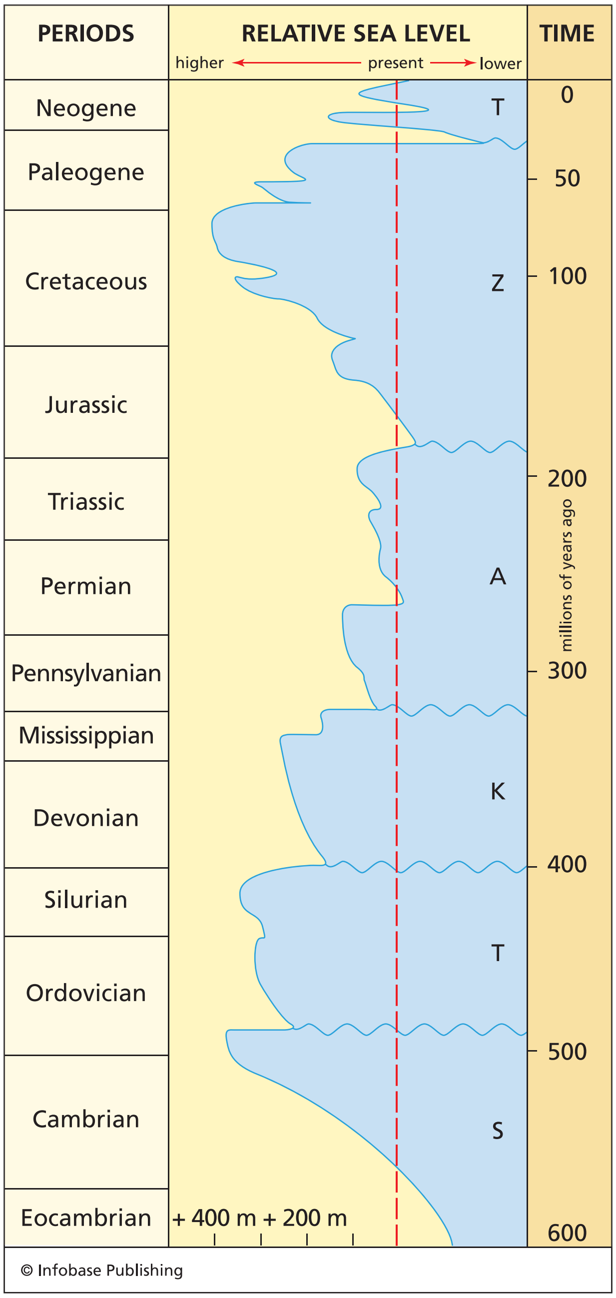
UNCONFORMITIES AND GAPS IN THE HISTORICAL GEOLOGICAL RECORD

Unconformities are regional surfaces that extend for large distances and represent periods of time missing from the geological record at that location. To interpret unconformities and understand what each means for the history of the region and Earth, it is important to determine how much of a time gap is represented, and what caused the stratum that would have been deposited in that interval to not be preserved. In some cases the stratum was once there and has since been eroded, and in other cases the stratum was never deposited.

Unconformities are classified into three major types. Angular unconformities separate rocks below that were deformed and tilted, then eroded, from a new sequence of flat-lying rocks on top (that can be later deformed). Regional angular unconformity surfaces show that there was a major deformation event, typically an orogenic or mountain-building episode, between when the lower and upper rocks sequences were deposited. The age of the unconformity is typically the approximate age of the mountain-building event. Disconformities represent periods of nondeposition or erosion, but have no angle between the lower and upper rock sequences. Disconformities may be harder to recognize than angular unconformities, and typically a prior knowledge of the stratigraphic sequence, biostratigraphic zones, or geochronologic data must be used to establish the existence of the disconformity. Nonconformities are boundaries where sedimentary strata are laid down upon underlying igneous or metamorphic strata, typically in a marine transgression. There may be long time gaps of no history preserved along nonconformity surfaces, typically hundreds of millions or even billions of years.

UNCONFORMITY BOUND SEQUENCES

Understanding of stratigraphy underwent a major change in the 1950s when the American geologist Laurence L. Sloss (1913–96) proposed the concept of sequence stratigraphy. Sloss and many colleagues and subsequent workers recognized numerous large, laterally extensive rock units that they named sequences that are bounded by unconformities of global significance. Some of these unconformities are so significant that they are found in almost all shallow water deposits of that particular age around the world. Studies revealed that these always occur where sea level has dropped from high to low, and the overlying sequence is always transgressive. Sloss and coworkers used index fossils to show that these unconformities have the same age on all continents, and are clearly related to changes in sea level. Sea level has been as much as 1,200 feet (350 m) higher than at present, and as many as 650 feet (200 m) lower than present. By correlating different unconformity-bound sequences on the different continents, Sloss and coworkers produced curves that showed the relative height of the sea for the past 600 million years of Earth history.



Sea-level curve showing the global average sea-level height through Phanerozoic geologic time, along with the six main unconformity bounded sequences deposited during transgressive and sea level high–stands. These sequences include the Sauk (S), Tippicanoe (T), Kaskasia (K), Absaroka (A), Zuni (Z), and Tejas (T) sequences.

The simple and slow rise and fall of sea level through geologic time produces unconformity-bound sequences. When sea level is high, sediments accumulate on the continental shelf, and when sea level falls, the shelf is exposed and eroded, and the sediments move off the shelf, producing an unconformity. When sea level rises again the new sequence is transgressive, deposited unconformably over the eroded shelf.

The history of the Earth and its life-forms has been based largely on the study of the stratigraphic record as described above, and by correlating the ages of different events such as changes in sea level from continent to continent using index fossils, fossil zones, geochronology, and a few other timescales such as the magnetic polarity timescale, geochemical timescales, and data from other fields such as plate reconstructions using paleomagnetism, paleoclimate, and paleoenvironmental reconstructions. From this, geologists have been able to piece together a robust history of the planet Earth, although there is still much to be learned and debated by generations of future geologists.

BIOGEOGRAPHY AND PALEOGEOGRAPHY

Biogeography is the study of the geographic distribution of plants and animals, and paleogeography is the study of the past distribution of plants, animals, landmasses, mountains, basins, and climate belts. The distribution of organisms may be explained by one of two general theories. The dispersal theory in biogeography states that a specific group of organisms was created at an initial center spot and radiated outward, during which time specific lineages evolved as they migrated. An alternative model is called vicariance biogeography, where initially primitive groups were widely distributed and were broken up by processes such as rifting and divergent plate tectonics, leading to evolution in individual isolated groups. Both examples have been shown to explain the distribution of species in different cases.

In the following sections of this entry the principles of historical geology and stratigraphy are used to discuss a brief history of the planet Earth and life. The discussion is focused mostly on North America and events that affected North America, but examples from around the planet are brought in to the discourse as appropriate.

PRECAMBRIAN GEOLOGIC HISTORY

The oldest rock record on Earth belongs to the Precambrian, including all rocks formed before 543 million years ago, making up about 80 percent of Earth history. The Precambrian is divided in different ways in different parts of the world. The most common usage is to call the youngest period in the Precambrian the Ediacaran (although it is also known as the Vendian, and in China the Sinian), ranging from 650 to 543 million years ago. This period is named after the Ediacaran Hills in Australia, where fossils from this age are exceptionally well preserved. This was preceeded by the Proterozoic, from 2,500 million to 650 million years ago, divided into the Paleoproterozoic (2.5–1.6 Ga, or billion years ago), the Mesoproterozoic (1.6–1.0 billion years ago), and the Neoproteroic (1.Ga-543 Ma) equivalent, in some usages to the early, middle, and late Proterozoic. The Proterozoic was preceded by the Archean, from 2.5 billion years (Ga) ago to the age of the oldest known rocks (presently 4.2 Ga), and the Archean was preceded by the Hadean, the time from which there is no preserved geologic record.

ARCHEAN

In the Archean the surface of the planet looked very different than it does now. Life was limited to primitive bacteria, so the land had no vegetative cover. The Earth was also producing more heat in the Archean than it is now, so it is likely that heat loss mechanisms, particularly plate tectonics, were operating much more vigorously then than now, with more seafloor volcanism, perhaps greater ridge length, and faster plate motion.

Precambrian rocks form about 50 percent of the continental crust, and most of these are preserved in stable cratons. One of the best-known cratons is the Canadian shield, which extends from the northern United States to northern Canada, although much of it is covered by a thin veneer of younger sedimentary rocks. Maps of North America reveal that the continent is made up of old continental cratons surrounded by Proterozoic and younger orogenic belts representing places where oceans have closed, bringing the cratons together. Most of these cratons were parts of older continents that broke up and then reassembled, by plate tectonic mechanisms, to form the current distribution in the continent.

Most cratons are made of two fundamentally different suites of rocks, including granite-greenstone terranes and granulite-gneiss belts. Granite-greenstone terranes consist of arcuate belts of metamorphosed volcanics and sediments in an overall terrane consisting of 80 percent granitoids and gneisses. Most of the greenstone (volcanic) belts in these terranes are 3–30 miles (5–50 km) wide, and 60–200 miles (100–300 km) long. Most of the greenstone belts in these terranes include gabbro, pillow lavas, banded iron formations, and a type of muddy sandstone called greywacke. Greenstone belts and granite-greenstone terranes show complex structure with many faults and folds, and are metamorphosed to greenschist to amphibolite facies. These resemble younger island arc, accretionary prism, and ophiolitic rocks. Thus Archean granite-greenstone terranes formed by the generation and collision of island arcs, with folds and thrusts formed during the collision stage.

The other main type of Archean terrane is known as the high-grade granulite-gneiss assemblage, and examples include much of Greenland and Labrador, Scotland, southern India, and the Limpopo Province of southern Africa. These provinces contain assemblages of rocks similar to those in granite-greenstone terranes, but the assemblages have been buried to 20–30 miles (35–50 km) depth and are now strongly metamorphosed. The strong deformation and metamorphism in granulite-gneiss belts, plus their common location between older cratonic blocks, suggests that they represent places where continents have collided and are now deeply eroded. As such, granulite-gneiss belts provide natural laboratories to study what happens deep in the crust during continental collision events. High-grade gneiss complexes are also common in Proterozoic terranes (such as the Grenville Province), and are presently forming beneath the Himalayan Mountains, where India and Asia are colliding.

PROTEROZOIC

The Proterozoic rock record shows many features that suggest that large continents were present in this interval, including the first appearance in the geological record of very thick and abundant mature quartz sandstones, although some smaller examples are known from the Archean. These sedimentary rocks include well-sorted quartzites and quartz-rich graywackes, and indicate long periods of abrasion on stable continental shelves, and in some cases are depositionally related to abundant limestones that contain shallow-water fossils called stromatolites. These types of sedimentary assemblages indicate long-term sedimentation on a big stable continent, and are considered to mark the time when many small plates characteristic of the Archean graded into larger plates of the Proterozoic and younger times.

PRECAMBRIAN ATMOSPHERE, OCEANS, AND CLIMATE

The compositions of the Earth's early atmospheres and oceans are not well known, but most models fall into two groups. One is that the early atmosphere was relatively oxygen free (anaerobic), and the other, that it was aerobic, or had oxygen levels approaching modern values.

The early anaerobic atmosphere-ocean model was suggested by biochemists to support their model for the origin of life. This is supported by many dark-colored Archean sedimentary rocks that contain unoxidized carbon, iron sulfides (FeS_2), and iron carbonate ($FeCO_3$) minerals. These minerals should have been oxidized if oxygen were present, although some conditions, such as rapid sedimentation, allow these minerals to exist under present atmospheric conditions. Some Archean terranes also contain copper, manganese, zinc, vanadium, and uranium in their least oxidized states, supporting an early, anaerobic atmosphere. The anaerobic model suggests that any oxygen produced by early photosynthesis or dissociation of water in the upper atmosphere was caught in oxygen sinks and ended up making water (H_2O) and carbon dioxide (CO_2).

The early aerobic (oxygen-rich) atmosphere-ocean model notes that stromatolites were abundant by 3.4 Ga, and these produced a lot of oxygen. This model notes that most of the unoxidized minerals found in Archean sediments can also be found in much younger sediments, and are found in oxygen-poor environments such as swamps. Also oxidized Archean soils and rocks have been found, including some more than 2.6 billion years old in southern Africa. There are other models that suggest that the atmosphere saw a slow increase in oxygen, from low levels to higher from Archean times to present.

Present models for the climate in the Precambrian are changing as new evidence is accumulating. Most models suggest that there was more CO_2 in the atmosphere, so perhaps the climate was warmer, with more acid rains on the surface changing the weathering conditions. At times it seemed the Earth was either all hot, or all cold, with some periods of global glaciations such as a major glaciation in which most of the planet's water was locked up in ice between 700 and 800 million years ago.

ORIGIN OF LIFE

The Earth is believed to be unique in the solar system in that it supports life, yet how life appeared is still unknown. A popular model for the origin of life was formulated in the 1920s. This model suggests that life originated as a consequence of chemical reactions on the early, nonliving Earth. The planet naturally contains a lot of carbon, hydrogen, oxygen, and nitrogen, the major building blocks for life in most organisms. Water is a universal solvent, and early ideas for the origin of life used that property to suggest that the chemical elements for life may have combined into more and more complex molecules, until finally life and organisms emerged.

All life on Earth shares a common chemical system of proteins and nucleic acids. The nucleic acid DNA can copy itself, and it carries a code that directs which proteins the organism assembles. The specific proteins that are assembled determine the structure and function of each cell and, ultimately, what kind of organism it turns into. The DNA code itself is so complicated that it can be rearranged in 4 × 10^{109} different ways. The origin of life, however, lies in the synthesis of the monomeric components of the proteins—the amino acids. The proteins are what directly determine an organism's characteristics.

The origin and production of amino acids required special conditions on the early Earth. They needed elevated temperature, high-energy source, and appropriate chemical elements. Experiments first done by Stanley L. Miller (American chemist and biologist, 1930–2007) and Harold C. Urey (American chemist, 1893–1981) in 1953 at the University of Chicago show that a primordial soup made of methane, ammonia, hydrogen, and water can, if exposed to electrical discharges similar to ultraviolet light, give rise to amino acids and nearly all the complex organic molecules essential to DNA. These alone do not, however, constitute life. These kinds of "hot soup" environments have been found in hot springs and volcanic lakes. An alternative theory on the origin of complex organic molecules (and life in some models) is that they came to Earth from outer space by meteorite and comets, having formed somewhere else.

Complex organic molecules including amino acids do not constitute life. After the simple amino acids form, it is no easy task to combine them into larger molecules and complex molecules necessary for life. These need additional stimuli, such as hot acidic water, or ultraviolet radiation, or perhaps lightning. A mechanism for initiating the ability for molecules to transmit information so that they can replicate themselves is also necessary. One idea is that this may have first been done on the surfaces of clay minerals, such as those found in some submarine hot spring environments such as those along the mid-ocean ridges. Somehow, in the early Precambrian, life emerged from these complex organic molecules and simple amino acids, but the origin of life remains one of life's biggest mysteries.

EMERGENCE OF PHOTOSYNTHESIS

The first single-celled organisms were heterotrophs; they could not manufacture their own food. These organisms consumed the inorganically formed amino acids or other chemicals existing in their immediate environment. These early organisms received energy from these amino acids by fermentation, the processes of breaking down food molecules (sugars) through a series of chemical steps, into carbon dioxide and alcohol. When photosynthesis began, organisms became able to manufacture their own food from inorganic elements, and they became autotrophs, typically following the reaction

$$CO_2 + H_2O + \text{light} \rightarrow CH_2O \text{ (food)} + O_2$$

Photosynthesizing organisms thus produced food for other heterotrophs and also released oxygen into the atmosphere. The exact timing of when organisms became able to produce chlorophyll is unknown, but the oldest record of chlorophyll is found in 3.5 billion-year-old stromatolites from Australia.

LIFE IN THE PRECAMBRIAN

The earliest known fossils are found in 3.5 billion-year-old cherts of the Warrawoona Group at North Pole, Australia. The fossils consist of stromatolites that formed reeflike mounds made of small, single-celled organisms called cyanobacteria, which are still common today. Stromatolites are known from many other Archean locations, and they are essentially the only macro-scale fossil found in Archean rocks. There are a variety of microscopic organisms known, but most of these fall into varieties of single-celled organisms such as cyanobacteria.

The first truly diverse fauna is found in the 1.8–1.6 billion-year-old Gunflint Formation on the north shore of Lake Superior. The Gunflint Formation contains layers of stromatolites, but between the stromatolite layers many new species of cyanobacteria have been found. The Gunflint contains the first possible eukaryotic cells, containing a nucleus, as opposed to all earlier cells, which were prokaryotic and contained no organized nucleus. This represents a very significant evolutionary advance.

The late Precambrian had a more diverse fauna and saw the first definitely eukaryotic cells, found in the 1.3 billion-year-old Beck Springs Dolomite of Death Valley, California. In this period stromatolites became very abundant, and some grew to enormous sizes, some tens of feet (several m) across. Trace fossils also first appeared in the late Precambrian in the form of worm burrows from the late Precambrian rocks at the base of the Grand Canyon Series.

Rocks of the Ediacarian (also known as the Vendian, Sinian, and Eocambrian) range between 700 million years and 543 million years old at the base of the Cambrian and the Paleozoic. This period is named after fossil-rich beds in the Ediacarian Hills of Australia, containing a wide variety of fossils of jellyfish (*Coelenterate medusae*), sea fans (octocorals), worms, and other species without skeletons. All of the Ediacarian fauna became extinct at the end of the period, and none shows any relationship to any younger fauna. There is a 200-million-year break in the fossil record between Precambrian stromatolites and the diverse plant and animal fossils in the Ediacaran Hills, and in this short gap of time for which no record is known, life had to change dramatically from the single-celled organisms that had inhabited the Earth for the past 3 billion years to complex life-forms found in these strata. To accomplish this the eukaryotes had to clump together in colonies; become consumers of food rather than manufacturers; develop specialized cells for reproduction, locomotion, and other functions; and develop a body sack with tissues and organs.

LATE PRECAMBRIAN PALEOGEOGRAPHY AND TECTONICS

In the late Proterozoic North America was part of the large supercontinent Gondwana that included Antarctica, Australia, India, Africa, Baltica, and many other cratons. By the Late Proterozoic this supercontinent began rifting apart, forming narrow seas similar to the present-day Red Sea between Africa and Arabia. These much older narrow seas were between North America and Antarctica and evolved into major oceans. Huge amounts of subsidence along the margins of these rifts formed very thick passive margin sedimentary wedges. By the end of the Precambrian all the margins around North America were passive, as the other continents drifted away. These and other passive margins formed during the breakup of the late Precambrian supercontinent and contributed to a general global rise in sea level as the amount of young ridges was large, and the average elevation of continents was decreased by continental extension, placing a larger volume of continental material below sea level and displacing an equivalent volume of water onto the continents in a global transgression.

EARLY PALEOZOIC HISTORY

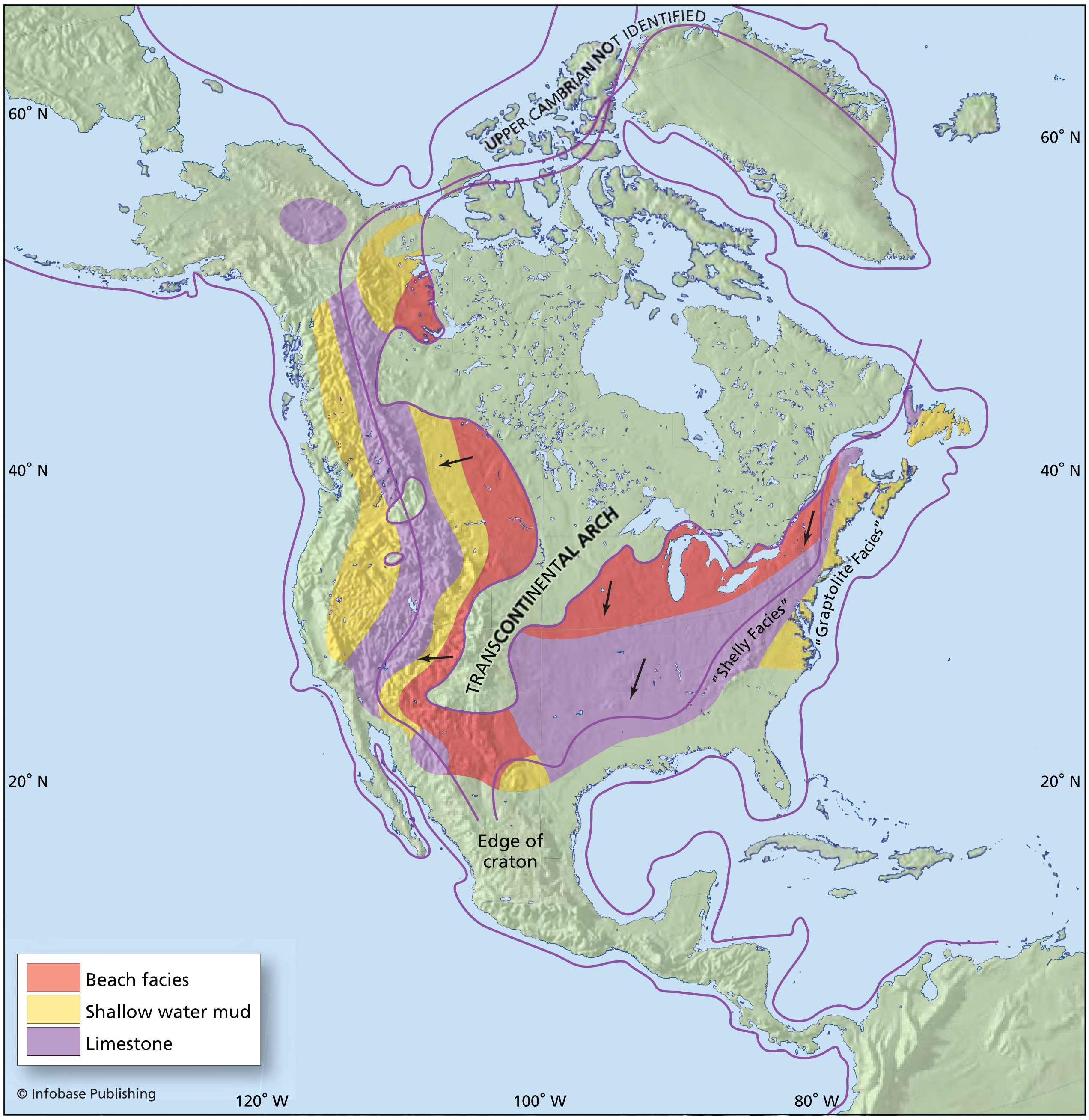
One of the greatest changes in Earth history is marked by the Precambrian-Phanerozoic transition. At this time the Earth witnessed the first widespread appearance of organisms with hard shells, and there was a huge adaptive radiation unparalleled in the rest of Earth history. By this time most of the cratons on the planet had formed and large continents existed, and plate tectonics had already been through several supercontinent cycles.

The history of the early Paleozoic can be interpreted from shallow seas that repeatedly flooded the cratons and from orogenic belts on the margins where island arcs and other terranes collided with and were sutured to the cratons. The principles of sequence stratigraphy prove useful for interpreting the history of the Paleozoic, as this era is marked by many transgressions and regressions caused by global rise and fall of sea level, and these formed several globally recognized unconformity-bounded sequences.

SAUK TRANSGRESSION

From Ediacarian through Cambrian times, sea level was constantly rising until it covered almost all of the cratons. On North America all but the central part of the Canadian shield was covered by shallow seas. The Cambrian isopach map shows a prominent feature called the transcontinental arch, thought to have formed by the bending of the North American plate under the great weight of the sedimentary sequences deposited on the margins of the craton. The distribution of Cambrian sedimentary facies around this arch shows that the facies are generally parallel to the arch, and that sand facies are generally next to the arch whereas deeper water shale and limestone facies are further offshore, showing that this is an original feature and not formed by erosion. The name given to the Eocambrian through late Cambrian rise of sea level is the Sauk transgression, which formed a shallow or epeiric sea over more than 75 percent of North America. During this period sea levels rose about one foot (0.3 m) every 20 years. As the seas rose they deposited a layer of quartz-rich sandstone over an unconformity that migrated toward the center of the craton with time, forming one of the major transgressive sand sequences of the past 500 million years of Earth history. Most of these sands were derived from the previous 500 million years of weathering products that accumulated on the cratonic interior of North America, and as the sea level rose, the high energy beach environment reworked these soils, sands, and other products in the regolith to a stable quartz-rich assemblage now preserved as the basal transgressive sand. Many of the sand grains in this basal quartzite are very rounded, and well sorted (meaning they have similar size to each other), suggesting that some of them were derived from windblown sand deposits before they were transported by rivers and reworked in the high-energy beach environment.

As the transgression continued most of the craton soon became covered with water, and less sand was available to be eroded and contribute to the sediments being deposited in the Sauk transgressive sequence. At this time the climate was favorable to the production of carbonate sediments, and the major type of deposition in the Sauk sequence switched to carbonates by the beginning of the Ordovician. Before this time carbonates were already being deposited along the deeper, outer parts of the continental shelves and seas, and worked their way toward the center of the craton. These carbonates consist of limestone and dolostone, largely made of shell fragments, limey muds, algae, and carbonate-secreting organisms. One special type of carbonate is known as oolitic limestone, which consists of many sand-sized carbonate grains with a texture resembling onion skin. These carbonates form by rolling about on the seafloor in shallow agitated waters, continuously being precipitated around a hard nucleus. Oolites form in waters saturated with respect to calcium carbonate, typically



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Upper Cambrian map of sedimentary facies of North America showing areas of beach facies (red), shallow-water mud (yellow), limestone (purple), and deepwater facies

in areas of high evaporation and agitation, which releases carbon dioxide. The Sauk Sea was shallow, as indicated by sedimentary structures formed by waves, shallow water fossils called stromatolites, and rare mud-cracks indicating that the sea bottom was occasionally exposed to the air.

Thick limestone sequences of the Sauk sequence indicate that North America was located within about 20 degrees of the equator in the early Paleozoic, and the paleoequator must have run approximately up the center of the continent (with the continent drifting into that position by plate tectonics). The climate was subhumid, warm, and rainy.

The Sauk sequence was terminated abruptly about 490 million years ago when sea level suddenly dropped (on geological timescales, taking a few million years), leading to widespread erosion and the formation of a worldwide unconformity surface on top of the Sauk sequence.

Life in the Cambrian included worms (preserved largely as worm tubes), the first mollusks, echinoderms, sponges, archaeocyathids, and coelenterates, and saw the widespread development of hard skeletons, generally phosphatic. In all probability there were also a large number of soft-bodied organisms in the Cambrian seas, but conditions did not favor their preservation. The evolutionary step of forming skeletons was very important to organisms in the Cambrian. The outer skeleton (exoskeleton) offers protection from ultraviolet rays and predators. It is also possible to make larger organisms with the presence of a skeleton since the skeleton can support the larger structures and act as a base for the development of muscles, which are needed for mobility.

Other organisms common in the Cambrian seas included the trilobites, a bottom-dwelling scavenger creature that resembled the modern horseshoe crab. These were the most abundant organism in the Cambrian, including more than 600 genera, some of which make very good index fossils. The Archaeocyathids were also bottom-dwelling organisms, shaped like a vase, with a double skeletal wall. These became extinct at the end of the Cambrian. Brachiopods, resembling clams, and mollusks, forming caplike shells, were common in shallow-water settings of the Cambrian seas.

TIPPECANOE SEQUENCE

Sea levels rose again and deposited a new transgressive sequence, known as the Tippecanoe sequence, from 490 to 410 million years ago during the Ordovician and Silurian Periods. Life in the Ordovician changed drastically from what it was in the Cambrian, and a great number of organisms flourished in the Ordovician. This may be attributed to the large amount of continental submergence (under the shallow seas), which created a large number of ecological niches, and also from the mild, steady climate of the times. Trilobites were not as numerous in the Ordovician as they were in the Cambrian, and they were less abundant than the Brachiopods and Bryozoans. Other organisms saw major changes in the Ordovician. The phosphatic shells of brachiopods were beginning to be gradually replaced by calcareous shells, and mollusks (snails) experienced rapid evolution, with new groups appearing, including the cephalopod (Nautiloids), which appeared and went through a very rapid evolution, including the appearance of giant forms reaching 30–40 feet (9–12 m). Since the cephalopods were also common, they make excellent index fossils for the Ordovician. Bryozoans appeared for the first time, making hard skeletal structures out of calcium carbonate, and various types of corals appeared including the solitary rugose coral, and more colonial forms that gradually developed prismatic forms that allowed them to grow more closely together. Graptolites are distinctive index fossils since they were widely distributed and evolved quickly. Graptolites were probably floating colonies that resembled seaweed but are generally preserved as single blades about a quarter inch to inch (0.5–3 cm) long. The Ordovician also saw the development of the first vertebrates, with fish containing armored plates found in a few fossil locations.

The shallow Ordovician seas had diverse ecosystems, and many of the modern ecosystem types such as continental shelves and reefs were firmly established in the Ordovician. At this time most life on Earth was based on the seafloor, between the shoreline and the deep abyssal plains. These included a number of different types of organisms, such as infaunal organisms that live within the bottom sediments, and epifaunal organisms that live on the bottom surface. Sessile benthic dwellers are those that are attached to some object on the bottom, whereas burrowers move through the sediment. Vagrant benthic organisms move around on the bottom, whereas deposit feeders eat small organic particles in the bottom sediments. Suspension or filter feeders capture and eat other organisms that float in the water, whereas planktonic organisms are passive floaters that live above the bottom. Nektons are actively swimming organisms, most of whom live in the photic zone, through which light can penetrate in the oceans.

Like the Sauk Sequence, the base of the Tippecanoe Sequence is marked by a pure quartz sandstone or quartzite, known as the St. Peter sandstone, forming a volume of quartz of some 4,800 cubic miles (20,000 km^3). The base of the St. Peter sandstone has slightly different ages in different places, being slightly older at the outer edges of the craton than in the interior of the continent, showing that unconformities can be time-transgressive, having different ages in different places.

Life in the Tippecanoe Sea was quite different from that in the Sauk Sea of the early Ordovician. The Tippecanoe ecosystems included diverse types of corals, stromatoporoids, bryozoan cephalopods, brachiopods, and armored fish. Upper Ordovician limestones are typically very shelly. The Upper Ordovician Seas reached all-time highs, representing the most complete flooding of continent ever in the geological past.

Middle to Late Orodovician deposition on the eastern side of the North American craton changed from limestone- to graptolite-bearing black shales, indicating a deepening of the water conditions. This deepening reflects a drastic and important change related to the approach of the Taconic island arc that would soon collide with the then North American craton in the Middle Ordovician. Other evidence also suggests that mountains were being uplifted on the eastern side of the craton during the Middle to Late

Ordovician. These include the presence of volcanic ashes interbedded with the shales, and the fact that the black shales are succeeded eastward and upward by a clastic wedge, containing sandstone, conglomerate shale, and so on eroded from mountains in the east. This clastic wedge represents a foreland basin, where many layers of sandstone, shale, and conglomerate were deposited by rivers that flowed out of the rising mountain range in the east, then redeposited by turbidity currents in deeper water environments during active deformation of the mountain range in a sequence of rocks known as flysch. The flysch, deposited during active deformation of the mountain range in the east is succeeded upward by deposits of molasse, which is nonmarine irregularly stratified conglomerate, sandstone, shale, and coal deposited in the late stages of mountain building.

TACONIC OROGENY IN THE APPALACHIANS

The deepening of the eastern shelf of North America, the presence of volcanic ash, and the clastic wedge of flysch and molasse all indicate middle to late Ordovician mountain building in the Appalachians. The cause of the abrupt deepening of the passive margin was by thrust loading from the weight of Appalachian Mountains being pushed up out of the Iapetus Ocean and onto the passive margin of North America during the collision of an island arc with the North American continent. During this mountain-building event, known as the Taconic Orogeny, the Taconic thrust belt was formed and in it pieces of an island arc and accretionary prism are preserved, representing an oceanic convergent margin that had been active in the Iapetus Ocean since the Cambrian, and collided with eastern North America in the Middle Ordovician, closing the oceanic segment between North America and the Taconic island arc.

POST-TACONIC PALEOGEOGRAPHY AND PALEOCLIMATE (SILURIAN AND DEVONIAN)

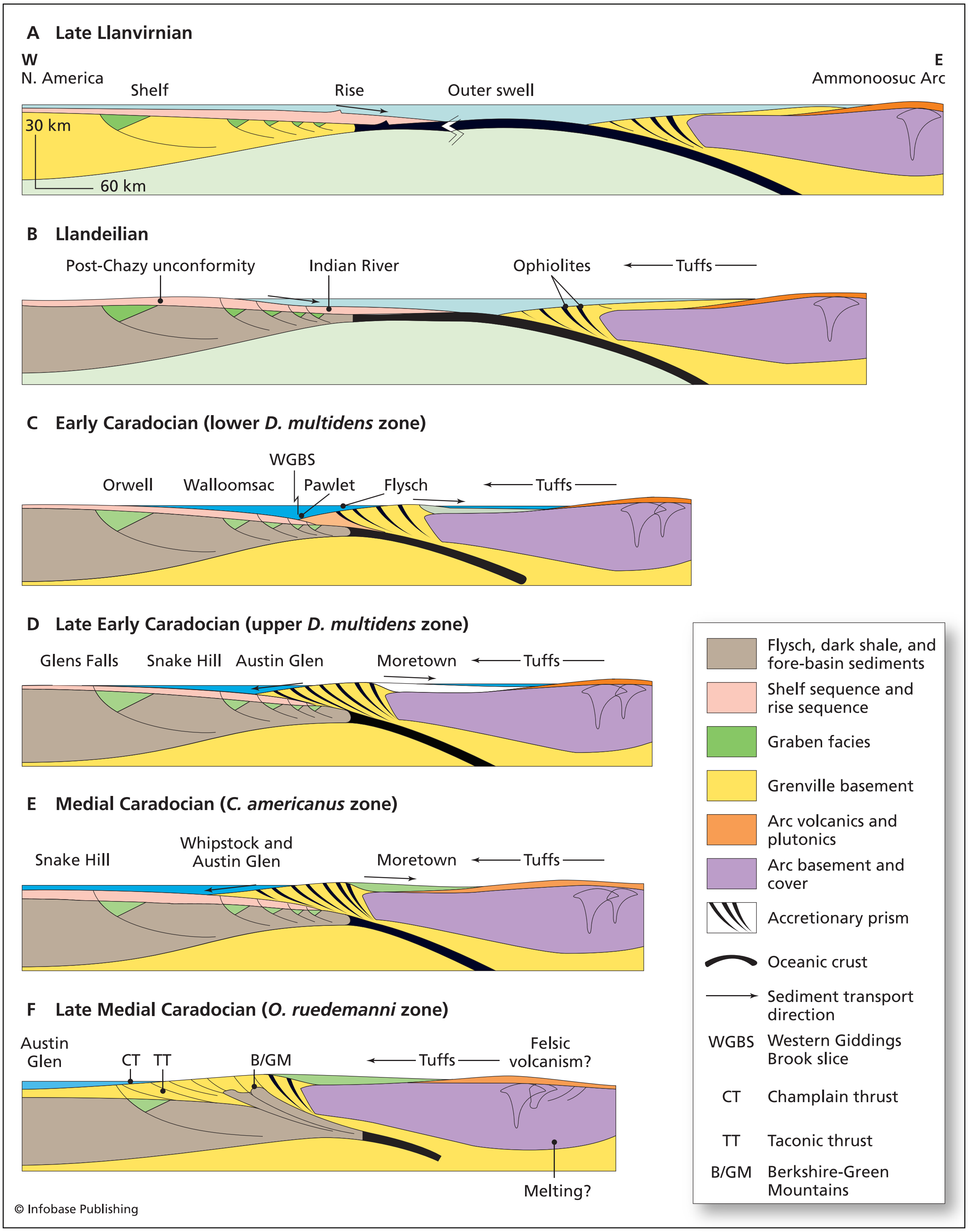
The Middle to Late Ordovician Taconic Orogen was eroded during early Silurian times, shedding early Silurian clastic sediments, including molassic sands and gravels. Erosion of the Taconic Orogen was fairly complete by middle Silurian times when the sea was again able to advance over the lands once covered with mountains.

The Silurian and Devonian atmosphere was strongly oxidizing, as indicated by abundant iron oxides in rocks of this age. Sediments deposited on the North American continent at this time include abundant evaporates, so the climate was likely warm for this period. In addition there are numerous reefs from North America, and modern-day reef systems form only at +/- 30° of the equator. Interestingly, the paleobiogeographic record shows that similar plants existed virtually everywhere at this time, suggesting that the Devonian climate was uniform on a near-global basis. Comparison with many past climates reveals that many were much warmer than Earth's present climate, lending support to the idea that the Earth can support very warm climates, and any changes that the planet may be experiencing presently from global warming could lead to major changes in planetary ecosystems.

DEVONIAN STRATA

In the late Silurian and Devonian a major regression affected most of the craton, exposing the underlying rocks to subaerial erosion, except for a few deep basins and narrow seaways. This major unconformity is overlain by a new transgressive sequence known as the Kaskaskia Sequence, which, like the two preceeding sequences, is marked by a basal quartz sandstone, overlain in turn by a thick carbonate sequence. Much of the continent was again covered by carbonate and shale deposition, and areas that saw enhanced subsidence during the Tippecanoe Sequence deposition also experienced greater than normal subsidence during the evolution of the Kaskaskia Sequence. These areas became deep basins, including the Michigan and Illinois basins in the midcontinent region.

Maps of the Upper Devonian sedimentary facies show a >1-mile (2-km) thick sequence of rocks on the eastern side of the craton known as the Catskill clastic wedge. This group of rocks provides evidence for another episode of mountain building or orogenesis in the Appalachians. The Catskill delta consists largely of molasse (conglomerate, red beds, mudstones) deposited by river systems in an alluvial fan/braided, meandering river complex, with the rocks derived from uplifted mountains in the east during the Devonian. The Catskill clastic wedge formed in front of the Acadian orogen, which was active (as shown by the ages of igneous rocks) from 360 to 330 million years ago. The Acadian Orogeny is thought to have been caused by closure of an ocean basin between North America and Avalonia (part of northwest Africa), along two subduction zones that dipped beneath both continental masses. The convergent margins collided, forming thick clastic wedges, then the collision continued as mostly sideways or strike slip motions through the late Devonian. The Catskill clastic wedge has an equivalent, but slightly older, sequence of rocks in Europe, known as the Old Red Sandstone, which also represents rapid erosion of a mountain range that formed by the north-south closure of an ocean basin in the Devonian. At this time North America and Europe were still connected in one landmass, and the ocean that closed between the combined North American/European continents and the colliding masses to the south (largely thought



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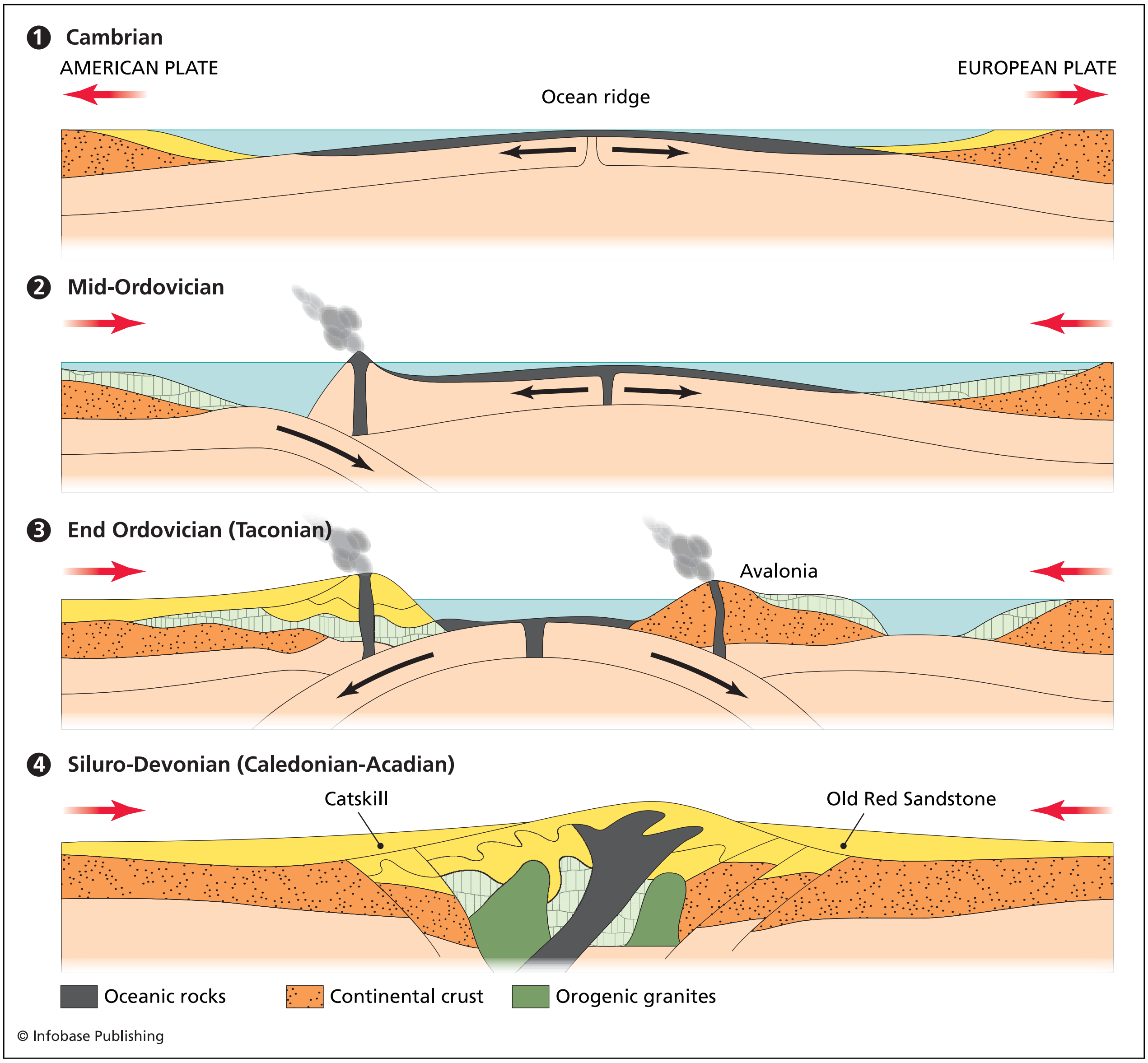
Geological evolution of the Taconic arc-trench collision during the Ordovician Taconic Orogeny in the Appalachian Mountains (modified from D. Rowley and W. S. F. Kidd, 1981) to be African and South America) was the remaining open part of the Iapetus Ocean that did not close during the Middle Ordovician Taconic Orogeny.

SILURIAN-DEVONIAN (436–360 MILLION YEARS AGO) HISTORY OF LIFE

In the Silurian and Devonian, organisms continued to evolve rapidly in the shallow sea that covered much of the continent, and like the late Ordovician, brachiopods and bryozoans were the most common organisms in the shallow seas. However, echinoderms became increasingly more important and abundant in the Silurian. By Silurian times the nautiloids and cephalopods had nearly disappeared, and the graptolites were virtually extinct. One line of descent of the nautiloids survived and evolved into groups of coiled ammonoids in the Devonian. These ammonoids were swimming and floating organisms, and they evolved rapidly, so they formed useful index fossils for this period. Another unusual but widespread group of animals, the small, toothlike conodonts, were abundant in this period, and these seem to represent some disaggregated parts of a larger type of floating or swimming organism.

In Silurian-Devonian times coral reefs became widespread and were populated mainly by rugose and tabulate corals. The Devonian was also important for the evolution of life in that fish experienced



Simplified cross section of the evolution of the Iapetus Ocean, including an Ordovician arc-continent collision and the Devonian collision with Avalonia, in the Acadian Orogeny widespread development, and the land was extensively invaded by plants. The Devonian has many examples of armored fish fossils, which show the development of internal skeletons, jaws, and evolved bodies better suited for swimming than their older Paleozoic counterparts. Many plants began to invade low-lying areas near the seas and lakes, and by the end of the Devonian, huge forests of thick trees covered much of the land, and the land became inhabited by insects, scorpions, and spiders that evolved from sea creatures. As an example, scorpions evolved from giant, three-foot (1-m) long eurypterids known as sea scorpions. By the late Devonian amphibians were crawling on the land, and these may have evolved from fish that crawled out of the sea.

LATE PALEOZOIC HISTORY

The last major deposition of carbonates on the North American craton was in Mississippian times, after which most of the North American continent has remained emergent, or exposed above sea level. The Mississippian was a time that saw vast proliferation of plants and animals across the continent, with many swamp deposits becoming peat bogs, and later when buried, being converted to coal. For this reason the time periods encompassing the Mississippian and Pennsylvanian are commonly referred to as the Carboniferous Period (355–290 million years ago).

The Late Paleozoic was also a time of continental amalgamation. North America finally collided with Africa and South America, forming Gondwana during the Appalachian or Alleghenian Orogeny (about 300 million years ago), and similar collisions worldwide formed the supercontinent of Pangaea (meaning all-lands, including the southern continents in Gondwana). The evolution of life progressed rapidly on land, with reptiles becoming strong and dominant on the land.

PANGAEA

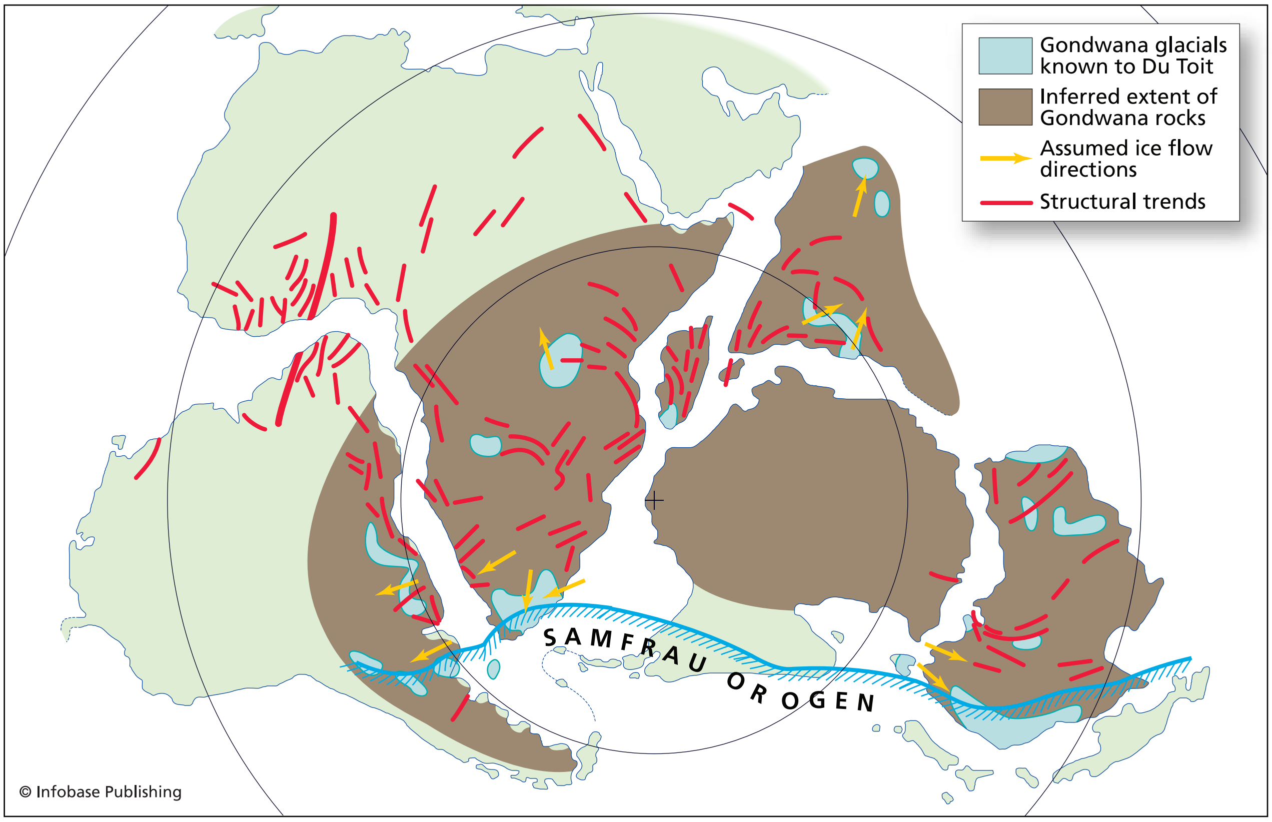
The Late Paleozoic saw the formation of Pangaea, which included the southern continents amassed in Gondwana and the northern continents grouped in Laurasia. Most of the evidence for the formation of the supercontinent of Pangaea comes from the southern continents, since nearly all of these contain nearly identical fossils and stratigraphy. These were studied extensively by Alex Du Toit from South Africa, and Alfred Wegener from Germany. Separately these two scientists pieced together evidence that eventually formed a compelling case for the existence of a Late Paleozoic supercontinent, encompassing virtually all of the planet's land masses. One of the most compelling arguments was Du Toit's observation of synchronous glaciations in Permian-Triassic times throughout Gondwana. He reasoned that if all of the continents were together, the patterns of glaciation and the volume of ice needed to explain the synchronous glaciation were reasonable, but if the continents had their present configuration, he calculated that there was not enough water on the planet to make all of the glaciers needed to cover the continents. Furthermore, geological matches of offset features across the oceans are restored when the oceans are closed. Later, paleomagnetic data were found to support the idea that the continents were formerly together and have been drifting apart since the breakup of Pangaea. Pangaea can now be reconstructed by looking at seafloor magnetic anomalies and restoring them to their older, late Paleozoic configuration.

HISTORY OF GONDWANA

Gondwana is the name given to the southern continents that amalgamated before they joined, as a group, to the northern continents of Laurentia to form Pangaea. Most of Gondwana was assembled in the period between 600 million and 400 million years ago, when many Archean cratons were joined together by suturing during closure of several ocean basins that lay between them, forming a series of orogenic belts across Africa, India, South America, Madagascar, Antarctica, and Australia known as the Pan-African belts. The last of these oceans to close was the Mozambique Ocean, which lay between western Gondwana (eastern Africa and South America) on one side and eastern Gondwana (Madagascar, India, Australia, Antarctica) on the other side.

The fauna of Gondwana (southern fauna) were distinct from those in North America (northern fauna) until the Devonian, when they became similar. In the late Paleozoic Gondwana collided with North America during the Appalachian (also called the Alleghenian) Orogeny, forming Pangaea. In addition southern South America, western Antarctica, and New Zealand collided with southern Gondwana to form orogenic belts there and further increasing the size of Pangaea. Like the Taconic and Acadian orogens these orogenic belts also have clastic wedges associated with them, recording the history of uplift and erosion of these mountain ranges.

Gondwana shows a remarkably similar stratigraphy on all of the major southern continents, grading from Devonian tillite (glacial gravels), through Carboniferous and Permian coal, Triassic red beds (sandstone and conglomerate), and Jurassic through Cretaceous volcanic rocks. The Devonian glacial tillites are remarkable rocks, found on all five southern continents. These were deposited unconformably on older rocks, and in many places the unconformity surface preserves scratches made by glaciers hundreds of millions of years ago. Boulders in the tillite also locally preserve glacial striations, plus isolated



Alex Du Toit's reconstruction of Gondwana showing areas affected by glaciation, striation directions, and other tectonic features

pebbles called dropstones, dropped by glaciers into otherwise muddy sediments, showing beyond reasonable doubt that these rocks were deposited in a glacial environment. Most of these tillites are interbedded with nonmarine rocks that bear a distinctive fossil assemblage including a seed fern called Glossopteris that inhabited low swampy areas next to glaciated terrane. The *Glossopteris* flora is found across much of Gondwana, and was used by Du Toit and Wegener to support their reconstructions of the late Paleozoic supercontinent. The Gondwanan stratigraphy grades up into Carboniferous to Permian coals, and then Triassic red beds, and finally Jurassic-Cretaceous volcanic rocks consisting mostly of basalt flows. These basalts are related to the breakup of Gondwana and Pangaea, and spreading of the modern oceans.

The animals of Gondwana included a great variety of reptiles, amphibians, fish, and invertebrates, some with key correlations across present-day oceans. Since these animals could not swim across such vast expanses of ocean, they provide additional supporting evidence that the continents were once joined together in a supercontinent mass. One of these animals, the Mesosauris, is a reptile that inhabited swampy areas and lived in present-day Brazil and southern Africa. Other animals that show similar matches across the oceans include the dinosaurs and the reptiles Lystrosaurus and Cynognathus.

The climate of Pangaea was diverse. There are glacial deposits in some places and times (e.g., the Permian), indicating a cold climate, and in other places and times there were swamps (*Glossopteris*) forming coals, indicating warm and swampy climate conditions, and in still other places evaporates formed, indicating hot, dry conditions.

The breakup of Pangaea began after the supercontinent had been united for about 200 million years and is marked by the eruption of the voluminous Jurassic and Cretaceous volcanics across the continents. Laurasia saw its breakup in the Late Triassic, as indicated by the formation of many rift basins such as the Triassic rifts along the eastern seaboard of North America. The rifts were filled with coarse sandstones and conglomerates as well as volcanic rocks, and they are generally colored red by the iron oxides formed during the intense hot climate of these times. Many of the rift basins preserve dinosaur footprints and other interesting fossils. As waters from the ocean occasionally spilled into the rifts during short-lived sea-level rises, evaporates formed as these waters evaporated in the hot climate. Rifting continued until the Middle Jurassic, when North

America or Laurentia began drifting apart from Gondwana and the supercontinent began breaking up all over. Some models suggest that the reason Gondwana broke up, and saw so much magmatism during breakup, is that it came to rest over a mantle hot spot that heated the lithosphere and caused the volcanics to erupt.

In the latest Cretaceous (about 66 million years ago, at the Cretaceous-Tertiary boundary) North America began moving away from Europe, opening the North Atlantic Ocean. During the evolution of Pangaea a large ocean, the Tethys Ocean, separated parts of the Northern and Southern continents (which were connected elsewhere). During breakup of Pangaea and opening of the Atlantic Ocean, the Tethys began closing and is now largely closed except for remnants in the Mediterranean, Black, and Caspian Seas.

CRETACEOUS-TERTIARY BOUNDARY AND THE CENOZOIC

The Cenozoic Era marks the emergence of the modern Earth, starting at 66 million years ago and continuing until the present. The Cenozoic includes the Tertiary (Paleogene and Neogene) and Quaternary Periods, and the Paleocene, Eocene, Oligocene, Miocene, Pliocene, Pleistocene, and Holocene Epochs. Many modern ecosystems developed in the Cenozoic, with the appearance of mammals, advanced mollusks, birds, modern snakes, frogs, and angiosperms such as grasses and flowering weeds. Mammals developed rapidly and expanded to inhabit many different environments. Unlike the terrestrial fauna and flora, the marine biota underwent only minor changes, with the exception of the origin and diversification of whales.

The Cenozoic began after a major extinction at the Cretaceous-Tertiary boundary, marking the boundary between the Mesozoic and Cenozoic eras. This extinction event was probably caused by a large asteroid impact that hit the Yucatán Peninsula near Chicxulub, Mexico, at 66 million years ago. Dinosaurs, ammonites, many marine reptile species, and a large number of marine invertebrates suddenly died off, and the planet lost about 26 percent of all biological families and numerous species. Some organisms were dying off slowly before the dramatic events at the close of the Cretaceous, but a clear, sharp event occurred at the end of this time of environmental stress and gradual extinction. Geochemical anomalies including the mineral iridium, generally found only in meteorites, have been found along most of the clay layers that mark this boundary, considered by many to be the "smoking gun," indicating an impact origin for the cause of the extinctions. An estimated one-half million tons of iridium are present in the Cretaceous-Tertiary boundary clay, equivalent to the amount that would be contained in a meteorite with a six-mile (10-km) diameter. Some scientists have argued that volcanic processes within the Earth can produce iridium, and an impact is not necessary to explain the iridium anomaly. However, the presence of other rare elements and geochemical anomalies along the Cretaceous-Tertiary boundary supports the idea that a huge meteorite hit the Earth at this time.

Many features found around and associated with an impact crater on Mexico's Yucatán Peninsula suggest that this site is the crater associated with the death of the dinosaurs. The Chicxulub crater is about 66 million years old and lies half-buried beneath the waters of the Gulf of Mexico and half on land. Tsunami deposits of the same age are found in inland Texas, much of the Gulf of Mexico, and the Caribbean, recording a huge tsunami perhaps several hundred feet (a hundred meters) high generated by the impact. The crater is at the center of a huge field of scattered spherules that extends across Central America and through the southern United States. The large structure is the right age to be the crater that resulted from the impact at the Cretaceous-Tertiary boundary, recording the extinction of the dinosaurs and other families.

The 66-million-year-old Deccan flood basalts, also known as traps, cover a large part of western India and the Seychelles. They are associated with the breakup of India from the Seychelles during the opening of the Indian Ocean. Slightly older flood basalts (90–83 million years old) are associated with the breaking away of Madagascar from India. The volume of the Deccan traps is estimated at 5 million cubic miles (20,841,000 km^3), and the volcanics are thought to have been erupted within about 1 million years, starting slightly before the great Cretaceous-Tertiary extinction. Most workers now agree that the gases released during eruption of the flood basalts of the Deccan traps stressed the global biosphere to such an extent that many marine organisms had gone extinct, and many others were stressed. Then the massive Chicxulub impactor hit the planet, causing the extinction including the end of the dinosaurs. Faunal extinctions have been correlated with the eruption of the Deccan flood basalts at the Cretaceous-Tertiary (K-T) boundary. There is still considerable debate about the relative significance of flood basalt volcanism and impacts of meteorites for the Cretaceous-Tertiary boundary. Most scientists would now agree, however, that the global environment was stressed shortly before the K-T boundary by volcanic-induced climate change, and then a huge meteorite hit the Yucatán Peninsula, forming the Chicxulub impact crater, causing the K-T boundary extinction and the death of the dinosaurs.

CENOZOIC TECTONICS AND CLIMATE

Cenozoic global tectonic patterns are dominated by the opening of the Atlantic Ocean, closure of the Tethys Ocean, and formation of the Alpine-Himalayan Mountain System, and mountain building along the western North American cordillera. Uplift of mountains and plateaus and the movement of continents severely changed oceanic and atmospheric circulation patterns, changing global climate patterns.

As the North and South Atlantic Oceans opened in the Cretaceous, western North America was experiencing contractional orogenesis. In the Paleocene (66–58 Ma) and Eocene (58–37 Ma), shallow dipping subduction beneath western North America caused uplift and basin formation in the Rocky Mountains, with arc-type volcanism resuming from later Eocene through late Oligocene (about 40–25 Ma). In the Miocene (starting at 24 Ma), the Basin and Range Province formed through crustal extension, and the formerly convergent margin in California was converted to a strike-slip or transform margin, causing the initial formation of the San Andreas fault.

The Cenozoic saw the final breakup of Pangaea and closure of the tropical Tethys Ocean between Eurasia and Africa, Asia, and India and a number of smaller fragments that moved northward from the southern continents. Many fragments of Tethyan Ocean floor (ophiolites) were thrust upon the continents during the closure of Tethys, including the Semail ophiolite (Oman), Troodos (Cyprus), and many Alpine bodies. Relative convergence between Europe and Africa, and Asia and Arabia plus India continues to this day, and is responsible for the uplift of the Alpine-Himalayan chain of mountains. The uplift of these mountains and the Tibetan Plateau has had important influences on global climate, including changes in the Indian Ocean monsoon and the cutting off of moisture that previously flowed across southern Asia. Vast deserts such as the Gobi were thus born.

The Tertiary began with generally warm climates, and nearly half of the world's oil deposits formed at this time. By the mid-Tertiary (35 Ma) the Earth began cooling again, culminating in the Ice House climate of the Pleistocene, with many glacial advances and retreats. The Atlantic Ocean continued to open during the Tertiary, which helped lower global temperatures. The Pleistocene experienced many fluctuations between warm and cold climates, called glacial and interglacial stages (the Earth is currently in the midst of an interglacial stage). These fluctuations are rapid—for instance, in the past 1.5 million years the Earth has experienced 10 major and 40 minor periods of glaciation and interglaciation. The most recent glacial period peaked 18,000 years ago when huge ice sheets covered most of Canada and the northern United States, and much of Europe.

The human species developed during the Holocene Epoch (since 10,000 years ago). The Holocene is just part of an extended interglacial period in the planet's current ice house event, raising important questions about how the human species will survive if climate suddenly changes back to a glacial period. Since 18,000 years ago the climate has warmed by several or more degrees, sea level has risen 500 feet (150 m), and atmospheric CO_2 has increased. Some of the global warming is human induced. One scenario of climate evolution is that global temperatures will rise, causing some of the planet's ice caps to melt and raising the global sea level. This higher sea level may increase the Earth's reflectance of solar energy, suddenly plunging the planet into an ice house event and a new glacial advance.

See also CLIMATE; CLIMATE CHANGE; GEOCHRONOLOGY; NORTH AMERICAN GEOLOGY; PALEOMAGNETISM; PALEONTOLOGY; PLATE TECTONICS; SEQUENCE STRATIGRAPHY; STRATIGRAPHY, STRATIFICATION, CYCLOTHEM; SUPERCONTINENT CYCLES.

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Holmes, Arthur **(1890–1965) English *Geochronologist and Geologist*** Arthur Holmes is considered to be the father of geochronology and study of the age of the Earth. He was the first to complete a uranium-lead radiometric dating experiment to determine the age of a rock. He was one of the early proponents of the model of continental drift at a time when most of the scientific community was strongly against the idea, and in 1956 he received one of geoscience's highest awards, the Wollaston Medal, and also has the European Geoscience Union's "Arthur Holmes Medal" named after him.

DEBATE ON THE AGE OF THE EARTH

Arthur Holmes was born on January 14, 1890, in Gateshead, England, to a cabinetmaker David Holmes and a former schoolteacher Emily Dickinson. Gateshead High School provided Arthur with a strong background in the sciences and an opportunity to develop his musical abilities in the Operatic Society. His teacher introduced him to the age of the Earth debate that had been recently refueled by the discovery of radioactivity. In 1897 Lord Kelvin (1824–1907), a professor of natural history at Glasgow University and an eminent expert of thermodynamics, announced his newest estimation for the age of the Earth. Believing that the Earth had been gradually cooling from its molten genesis, Lord Kelvin calculated that the Earth's crust consolidated 20 million years ago, based on experimentally determined temperatures at which rocks melt and their rate of cooling. Now his long accepted estimation was being challenged, and not by geologists, who seemed to be intimidated by his stature, but by physicists.

Near the end of the 19th century the age of the Earth was a popular topic for research and discussion among geologists, who thought the Earth was an order of magnitude older than Lord Kelvin claimed. Professor John Joly of Trinity College, Dublin, supported the salinity method for estimating the age of the Earth. As the newly formed globe cooled, water condensed and formed the oceans. The water would initially be pure, but as rocks decomposed and washed over the land into the seas, the water would become saltier. Using this assumption, if one measured the salinity of the oceans at two time points separated by a few hundred years, then one could extrapolate back to estimate how much time has passed since the water was pure, that is, when the Earth's crust solidified. From the rate calculated for salt accumulation from erosion, Joly estimated the oceans to be more than 90 million years old. One criticism of this method was that it required the rocks to lose more salt than they ever contained to supply the calculated amounts to the oceans each year. Alternatively, Irish geologist Samuel Haughton employed the simple concept that thicker strata took longer to form to estimate the Earth's age. After figuring that sediments accumulated on the ocean floor at a rate of one foot (30.5 cm) in 8,616 years, he estimated that it would require at least 200 million years, or possibly 10 times longer, to lay down the total thickness of rock covering the planet. Problems with this method included inaccurate estimations of the total thickness of rock on the Earth's surface and sedimentation rates that differed significantly according to time and place. Even without a satisfactory means of measurement, Lord Kelvin's revised approximation of 20–40 million years appeared to be a major underestimate.

Then in 1896 French physicist Henri Becquerel discovered natural radioactivity when he observed that uranium emitted invisible rays of energy. Polish physicist Marie Skłodowska Curie studied the emanations for her doctoral dissertation and found that thorium also emitted such rays, and furthermore, the emanations were a property of atoms and not due to a chemical reaction. Curie named the revolutionary phenomenon radioactivity, and she and her husband, Pierre Curie, proceeded to discover two new radioactive elements, radium and polonium. Ernest Rutherford (1871–1937) and Frederick Soddy (1877–1956) explained radioactivity as the result of the instability of an element that spontaneously emitted particles from its nucleus. For example, uranium released helium atoms as it decayed. In the process an element could transform into another element. Some radioactive elements had very long half-lives; uranium took 4.5 billion years to decay to half of its original amount. In 1905 Rutherford suggested that radioactive decay could be used as a geological timekeeper. Using uranium/helium ratios, he determined the age of a sample of pitchblende to be 90 million years, but he incorrectly assumed that helium did not escape over time.

Pierre Curie and colleague Albert Laborde announced in 1903 that radium emitted enough heat to melt its own weight in ice in less than one hour. This finding that radioactive elements generate heat refueled the debate over the age of the Earth. Lord Kelvin's calculations depended on the Earth's slow cooling in an absence of any external heat source, and these physicists claimed that radioactive elements within the Earth provided enough heat to make his calculations worthless. Holmes was intrigued by these scientists who challenged the authoritative Lord Kelvin and by the potential utility of this phenomenon called radioactivity. As a teenager, witnessing the debate between one of the world's most established scholars and a few lesser known but equally accomplished physicists made a great impression upon Holmes. Now, he was also interested in radioactivity, and these two curiosities would merge to become his lifelong passion, using radioactive decay to determine the age of the Earth.

A YOUNG GEOCHRONOLOGIST

Holmes earned a National Scholarship Award in physics and enrolled at the Royal College of Science in London in 1907. The curriculum required all students to take mathematics, mechanics, chemistry, and physics during their first year, and Holmes took an elective geology course in his second year. The president of the Geological Society, William Watts, taught the course and enticed Holmes to change his course of study during his third year. Fortuitously, Robert J. Strutt (1875–1947) from the Cavendish Laboratory at Cambridge University had joined the college at the same time Holmes enrolled. Strutt was one of the physicists who made public his belief that radioactive elements provided a source of heat sufficient to discredit Lord Kelvin's young estimation for the age of the Earth. Strutt invited Holmes to assist him in examining helium trapped in rocks following radioactive decay. He thought that if they could measure the amount of accumulated helium and establish its rate of production, then they could calculate the age of the rock. The concept seemed simple, but determining the rate of helium production was not a straightforward process. Because helium is a gas, an unknown but significant quantity escapes as it is produced, so only the minimum age could be estimated. (Uranium/helium measurements later were considered unreliable since the helium was not retained consistently.) After graduating from Imperial College (formerly the Royal College of Science) in 1910, Holmes assumed this research project with Strutt as a postgraduate student.

Across the ocean, American chemist Bertram Boltwood (1870–1927) had recently determined that lead was the final product of uranium decay, and he attempted to date several rocks using uranium/lead ratios. From 26 rocks he obtained ages ranging from 92 to 570 million years. Since helium could escape from rocks over time, he thought focusing on the end product would yield more accurate results. Unknown to chemists at the time, Boltwood's analysis was flawed because of the existence of several isotopes of both uranium and lead. From his results Boltwood constructed a rough list of geological ages.

Holmes was anxious to use radioactivity to measure the age of a rock, selecting a Devonian rock from Norway that contained 17 different radioactive minerals so he could check each result against the others. After crushing the rock, extracting the minerals, and chemically separating them for analysis, he determined the ratios of uranium and lead and estimated the rock to be 370 million years old. He analyzed several others, dating the oldest at 1,640 million years, then calculated ages of geological periods from measurements published by Boltwood. Holmes wrote up his results showing that as the ratio of lead to uranium increased, so did the age of the rock (since uranium decays into lead), but he wondered if some lead was already present, which would have rendered his analysis flawed.

Strutt presented Holmes's results in April 1911 at a Royal Society meeting, where fellow geologists seemed interested but were wary of the radiometric dating technique. They questioned whether it was acceptable to assume the uranium decay rate was constant, and had trouble accepting the possibility that the Earth was more than 1 billion years old. Though geologists were looking for evidence indicating the Earth was older than 20 million years and knew the old techniques relied on rates of nonuniform processes, they were expecting a value closer to 100 million years as suggested by rates of sedimentation and salt accumulation, the so-called hourglass methods.

MOZAMBIQUE

In 1911 Holmes obtained a position as a geological prospector for Memba Minerals Limited. After giving his research results to Strutt, Holmes left England for Mozambique in March, beginning a physically difficult six-month expedition in search of economically valuable minerals. While there, Holmes contracted malaria, and high fevers occasionally forced him to rest for several days. Lying in bed, he could not stop thinking about radiometric dating and contemplated how he could reconcile data obtained by radiometric methods with data calculated from sedimentation rates. Without access to geology textbooks or journals, he used his memory to approximate the amount of original igneous rocks from which sediments had been derived, then figured out how long it would have taken for the sediments to be deposited. His estimate was 325 million years since the base of the Cambrian period, not too far from the value of 543 million years that he obtained using radiometric methods. He wrote a friend asking him to publish his results.

Though prospecting for precious minerals was unsuccessful in Mozambique, during the trip Holmes developed a lifelong interest in Precambrian time and a new commitment to constructing a geological timescale. He collected zircons, minerals good for age determinations, and several samples of never-examined Precambrian rock types. As the prospectors headed home, Holmes became gravely ill with black water fever. The nuns at the hospital in Mozambique prematurely telegraphed news of his death to London, but Holmes miraculously recovered and arrived in Southampton in November 1911. He continued to suffer from bouts of malaria for years afterward.

THE PROBLEM WITH LEAD

In 1912 Imperial College offered Holmes a position as a demonstrator in geology, and in July 1914 the 23-year-old geologist married Margaret Howe. Holmes kept busy lecturing and researching the petrographical material he brought back from Mozambique. When World War I broke out in August, the military declared Holmes unfit for military service because of his recurring bouts of malaria. His contributions toward the war effort included making scaled topography maps for naval intelligence and researching alternative sources of potash, an ingredient of fertilizer formerly supplied to Great Britain by Germany.

To convince his contemporaries of the usefulness of radiometric dating, he composed *The Age of the Earth* (1913), a review of the historical methods for estimating ages of geological materials that also presented all the current related evidence and contrasted the results obtained by different techniques. In this book he pointed out problems with the other approaches and defended his own estimation of 1,600 million years based on uranium/lead measurements.

The possibility that "ordinary" lead, in existence since the formation of the Earth, was already present in the rock samples before any radioactive decaying took place was troublesome. Another difficulty in using lead measurements was that in addition to uranium, the radioactive element thorium also decayed to lead. To overcome this Robert Lawson, a friend from childhood who worked at the Radium Institute of Vienna, determined the atomic masses of the three lead isotopes, enabling one to adjust age calculations accordingly based on the proportions of each type.

Holmes thought he resolved a means to determine the age of rocks with accuracy, but he did not know yet that uranium also had another isotope. Uranium 238 makes up 99 percent of the total uranium, but uranium 235 decays at a faster rate, and Holmes unknowingly included its end product as part of the ordinary lead. This isotope hitch prevented skeptics from recognizing the promise of this new dating technique.

WORK IN THE PETROLEUM INDUSTRY

By the end of World War I Holmes had written three books but was still only a demonstrator at Imperial College. In 1918 the Holmeses had their first child, Norman, and a demonstrator's income was not sufficient to support the family. The Yomah Oil Company hired Holmes as chief geologist with the promise of a much larger salary. His family moved to Burma in November 1920 and settled in Yenangyaung, where Holmes spent two years frantically searching for new oil finds to save the struggling company. Loyalty to the company kept him working long after the then bankrupt company stopped paying him, and before they finally returned to England in late 1922, Norman died from severe dysentery.

Without an institutional affiliation, Holmes could not secure funding to continue his research. For a while he worked in a fur, brass goods, and knick-knack shop that he opened with Maggie's cousin. His marriage was deteriorating, but soon Maggie was pregnant with their second son, born in February 1924. The year Geoffrey was born, the University of Durham happened to be expanding its science programs and they needed a reader for geology. Holmes gratefully accepted the offered position. The following year he became head of the geology department, of which he was the only faculty member. He was a popular lecturer, and the few students who came through the geology department each year thought he was a fair teacher and a caring mentor.

THE POWERFUL ENGINE OF RADIOACTIVITY

While Holmes's major passion was finding absolutes for geological time, he was also knowledgeable about other subjects. In 1915 German meteorologist Alfred Wegener (1880–1930) proposed the theory of continental drift, suggesting all the continents once were part of an enormous supercontinent that broke into pieces leading to the present distribution of continental masses. This model was exciting because it explained many unusual geological (and biological and climatological) phenomena, but most geologists hesitated to accept it without a plausible mechanism. The English translation of Wegener's book *The Origin of the Continents and Oceans* in 1924 aroused a heated debate, and Holmes was among the few geologists progressive enough to entertain the idea.

Aware of the enormous energy provided by radioactivity, Holmes suggested that the intense heat generated by the radioactive decay of unstable elements within the Earth's interior was a sufficiently powerful engine for moving continents. The substratum, or mantle, was solid, but he thought that over millions of years it behaved like a thick liquid. Holmes proposed thermal convection as a means to dissipate the heat, causing the cooler material close to the surface to sink, leaving space for hotter, less dense material to rise into and fill. In December 1929 Holmes proposed to the Geological Society of Glasgow that convection currents were responsible for continental drift. He explained that as convection currents in the mantle cooled and descended, they could drag continents horizontally across the Earth's surface. "Radioactivity and Earth Movements," his seminal paper, was published in the *Transactions of the Geological Society of Glasgow* in 1931. Though Holmes had a respectable scientific reputation, his ideas were mostly ignored until the 1960s, when American geophysicists Harry Hammond Hess and Robert Sinclair Dietz independently proposed the concept of seafloor spreading, which in combination with continental drift has evolved into the well-supported theory of plate tectonics.

Holmes was invited to lecture around the world, including in the United States in 1932. He took advantage of this opportunity to solicit help in constructing a geological timescale from American scientists. His demanding schedule forced Durham to hire another lecturer in the geology department in 1933; they selected Doris L. Reynolds, a notable petrologist with whom Holmes had been having an affair since

1931. In 1938 Maggie died from stomach cancer, and Holmes married Reynolds in 1939.

A FOURTH ISOTOPE

Since his days in Mozambique Holmes wanted to develop a geological timescale with dates defining the beginning of each period and epoch. The work of previous geologists allowed for the construction of a geological column organized by characteristics of the layers of rock and by the distinctive index fossils contained within the strata. These historical developments permitted relative ordering but not the assignment of specific dates for the time periods. Holmes needed a framework on which to build and asked chemistry professor Fritz Paneth in Berlin for assistance. In 1928 Paneth developed a precise assay for measuring very small amounts of helium and used it to analyze two famous rocks from known geological periods: the Whin Sill from the late Carboniferous period and the Cleveland Dyke from the middle to early Tertiary period. Paneth dated the Whin Sill at 182 million years and the Cleveland Dyke at 26 million years, ages that seemed to agree with the geological evidence. (Today the Whin Sill and Cleveland Dyke are believed to be approximately 295 and 60 million years old respectively.) These two rocks did not have enough lead to determine lead ages as controls, but Holmes was anxious to make progress and confident that a geological timescale was possible.

Geologists were now more accepting of the longer estimates for the age of the Earth, which Holmes reported in his second edition of *The Age of the Earth* (1927) to be between 1,600 and 3,000 million years based on the uranium and lead measurements. The book also contained a geological timescale based on lead ratios and helium ratios, but two decades brought little progress—Holmes summarized all the computed mineral ages in a single short table.

The invention of the first mass spectrograph by English chemist Francis William Aston enabled the identification of isotopes with different atomic weights. Aston used his mass spectrograph to discover no fewer than 212 naturally occurring isotopes and was awarded the Nobel Prize in chemistry for 1922. The mass spectrograph evolved into the more advanced modern mass spectrometer that separates isotopes by passing them through a magnetic field that deflects them to different degrees based on their mass and the charge of the field. In the late 1920s Aston clearly identified three known lead isotopes, a finding with major implications for radioactive dating. He also unexpectedly noted that the isotope believed to be ordinary lead was in fact an end product from the decay of another less abundant uranium isotope that Rutherford helped identify as uranium 235. Rutherford estimated the uranium 235 decay rate, assumed that at the time of the Earth's formation uranium 235 and uranium 238 were present in equal amounts, and calculated the time it would have taken for the equal amounts of the two isotopes to decay to their current ratios. He obtained an astounding value of 3,400 million years, but his results and similar results from a few other geologists were mostly ignored.

If uranium 235 decayed to lead 207, then did so-called ordinary lead exist at all? In 1937 a physicist from Harvard University, Alfred Nier, began exploring the questionable existence of ordinary lead using a new mass spectrometer kept ultraclean to ensure no contaminating lead was present. He easily identified the three known lead isotopes, but he also observed a tiny amount of a fourth lead isotope with an atomic mass of 204 not produced by radioactive decay.

PRIMEVAL LEAD COMPOSITION

By the 1940s geologists had accepted the billion-year range for the age of the Earth, but no one had assigned absolute times to the geological timescale. One problem was that accurate ages could be obtained only from igneous rocks, since they contained high amounts of lead, but it was hard to know their geological age. Nier surmised that since two isotopes of uranium decayed to lead (uranium 238 decayed to lead 206 with a half-life of 700 million years, and uranium 235 decayed to lead 207 with a half-life of 4.5 billion years), comparison of both lead isotope growth rates to the constant value of the fourth isotope, lead 204, would reveal an accurate age. To test the validity of this lead-lead method, he dated 25 ancient lead ores with very low lead ratios and found the calculated ages from the different "clocks" generally agreed.

Holmes employed a novel approach for determining an accurate age of the Earth. His method depended on primeval isotope ratios, the ratios present during the Earth's genesis. Since uranium and thorium were formed, they have been decaying continually, while the amount of ordinary lead has remained stable. Since the primeval lead composition would have been trapped and fossilized inside minerals as the newly formed crust solidified, one should be able to locate minerals with ancient parts of the Earth's crust from which the primeval composition of lead could be identified. Then one could calculate the time elapsed since the Earth's primeval mix of lead isotopes began to be contaminated by radiogenic lead. With the assistance of a newly acquired Marchant calculating machine, Holmes used this method to calculate confidently the age of a rock sample from an ancient galena (lead ore) from Greenland to be 3 billion years. He rightly felt this was a defining moment in his efforts to date the age of the Earth.

Under the assumption that the galena represented primeval lead, Holmes used Nier's measurements to calculate more than 1,400 solutions for the age of the Earth. When he plotted the frequencies of each computed age, he obtained a well-defined peak at 3,350 million years. Though the rock samples that he used actually did not contain the primeval lead values, the mathematical approach he developed formed the basis of the one used today. Because the German Fiesel Houtermans used a similar technique, the method is referred to as the Holmes-Houtermans model for dating the Earth. By this time in 1946 geologists accepted isotope dating but still debated the best means for applying its use.

Next Holmes constructed a geological timescale that reconciled his new radiometric results with the hourglass estimations. He began by collecting information on sediment thicknesses from around the world, then plotted the thicknesses to scale for the whole geological column from the present day to the base of the Cambrian period. He incorporated dates calculated from Nier's data by using primeval lead ratios, plotted the five most probable ages as control points, and extrapolated to estimate dates for the bases of other geological periods. He published his results, "The Construction of a Geological Time Scale," in *Transactions of the Geological Society of Glasgow* in 1947, aware that accumulation rates were not constant. He frequently adjusted his scale to accommodate corrected information and to include additional data obtained by new techniques, and in 1959 he published "A Revised Geological Time Scale" in *Transactions of the Edinburgh Geological Society*. In 1953 Clair Patterson and Harrison Brown obtained accurate primeval lead isotope measurements from an iron meteorite formed at the same time as the Earth and computed the value of 4.55 billion years for the age of the Earth. Though in the last 50 years scientists have obtained new data and made adjustments to improve accuracy, the assessment of 4.55 billion years remains the currently accepted value.

FINAL YEARS

Having accomplished his two career goals of dating the Earth and constructing a geological timescale that could be applied to common rocks, Holmes concentrated on his professorial duties. In 1943 the University of Edinburgh appointed him regius professor of geology, a position subsidized by the king of England. The outbreak of World War II forced Holmes to reduce his geology course from one year to six months. Though it would have saved lecture time to assign students reading material before coming to class, no geology textbook contained information about the recent developments in the field, such as radiometric dating and continental drift. Holmes took it upon himself to compose a book based on his lecture notes. When he published *Principles of Physical Geology* in 1944, it became an immediate best seller and was reprinted more than 18 times during the following 20 years.

Holmes became ill in 1948 and lost all interest in his work. The doctor ordered complete rest, and he and his wife spent the summer in Ireland. After recovering, Holmes focused on Precambrian geology and revised Africa's geological map based on radiometric dates. His heart began to deteriorate, and in 1956 he retired from the University of Edinburgh.

The distinguished geologist belonged to numerous scientific organizations and received many honors and awards during his career. The Geological Society of London gave Holmes their Murchison Medal in 1940 and their highest award, the Wollaston Medal, in 1956. The Geological Society of America awarded Holmes their Penrose Medal in 1956 for his outstanding contributions in the science of geology. In 1964 Holmes received the Vetlesen Prize, the greatest honor for a geologist, for his "uniquely distinguished achievement in the sciences resulting in a clearer understanding of the Earth, its history, and its relation to the universe." His health was too frail to travel to Columbia University for the award ceremony, but he did find the strength to tackle one more major project, revising *Principles of Physical Geology*. He finished just a few months before he died of bronchial pneumonia on September 20, 1965, in London.

Arthur Holmes was a quiet man but did not avoid the controversial topics of geology in his day, in particular, the antiquity of the Earth and continental drift. His background in physics convinced him radiometric dating was the most accurate means for determining the age of rocks and the Earth. This made him the right man for the job of providing actual ages for Earth's geological episodes. The implications of Holmes's estimate for an ancient Earth were widespread; they forced astronomers to reexamine the age of the universe and gave biologists reasonable time to allow for the occurrence of evolutionary processes. Though his contributions toward advancing the idea of drifting continents are often overlooked, Holmes was the first to propose convection currents as a plausible moving force. Today scientists believe the Earth formed 4.55 billion years ago because the father of geological time had a passion for seeking the truth and dedicated himself to laying the groundwork for using the natural geological clocks within the rocks.

See also GEOCHRONOLOGY; HESS, HARRY; PRECAMBRIAN.

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hot spot A hot spot is a center of volcanic and plutonic activity not associated with an arc and generally not associated with an extensional boundary. Most hot spots are 60–125 miles (100–200 km) across and are located in plate interiors. A few, such as Iceland, are found on oceanic ridges and are identified on the basis of unusually large amounts of volcanism on the ridge. Approximately 200 hot spots are known, and many others have been proposed but their origin is uncertain.

Hot spots are thought to be the surface expression of mantle plumes that rise from deep in the Earth's mantle, perhaps as deep as the core/mantle boundary. As the plumes rise to the base of the lithosphere, they expand into huge, up to 600-mile (1,000-km) wide plume heads, parts of which partially melt the base of the lithosphere and rise as magmas in hot spots of plate interiors.

HAWAIIAN HOT SPOT

The most famous hot spot in the world consists of the chain of the Hawaiian Islands, extending northwest to the Emperor Seamount chain. Hawaii is a group of eight major and about 130 smaller islands in the central Pacific Ocean. The islands are volcanic in origin, having formed over a magmatically active hot spot that has melted magmatic channels through the Pacific plate as it moves over the hot spot, forming a chain of southeastward younging volcanoes over the hot spot. Kilauea volcano on the big island of Hawaii is the world's most active volcano and often has a lava lake with an actively convecting crust developed in its caldera. The volcanoes are made of low-viscosity basalt and form broad shield types of cones that rise from the seafloor. Only the tops are exposed above sea level, but if the entire height of the volcanoes above the seafloor is taken into account, the Hawaiian Islands form the tallest mountain range on Earth.

Halemaumau crater on Kilauea, Hawaii *(G. Brad Lewis/Riser/Getty Images)*

Pillow lava off the coast of Hawaii, formed when lava from the Hawaiian hot spot flowed into the ocean *(OAR/National Undersea Research Program/Photo Researchers, Inc.)*

The Hawaiian Islands are part of the Hawaiian-Emperor seamount chain that extends all the way to the Aleutian-Kamchatka trench in the northwest Pacific, showing both the great distance the Pacific plate has moved and the longevity of the hot spot magmatic source. From east to west (and youngest to oldest) the Hawaiian Islands include Hawaii, Maui and Kahoolawe, Molokai and Lanai, Oahu, Kauai, and Niihau.

The volcanic islands are fringed by coral reefs and have beaches with white coral sands, black basaltic sands, and green olivine sands. The climate on the islands is generally mild, and numerous species of plants lend a paradiselike atmosphere to the islands, with tropical fern forests and many species of birds. The islands have few native mammals (and no snakes), but many have been introduced. Some of the islands such as Niihau and Molokai have drier climates, and Kahoolawe is arid.

ICELAND HOT SPOT

The mid-Atlantic ridge rises above sea level on the North Atlantic island of Iceland, lying 178 miles (287 km) off the coast of Greenland and 495 miles (800 km) from the coast of Scotland. Iceland has an average elevation of more than 1,600 feet (500 m), and owes its elevation to a hot spot interacting with the midocean ridge system beneath the island. The mid-Atlantic ridge crosses the island from southwest to northeast and has a spreading rate 1.2 inches per year (3 cm/yr), with the mean extension oriented toward an azimuth (compass direction) of 103 degrees east of north. The oceanic Reykjanes ridge and sinistral transform south of the island rises to the surface and continues as the Western Rift zone. Active spreading is transferred to the Southern Volcanic zone across a transform fault called the South Iceland Seismic zone, then continues north through the Eastern Rift zone. Spreading is offset from the oceanic Kolbeinsey ridge by the dextral Tjornes fracture zone off the island’s northern coast.

During the past 6 million years the Iceland hot spot has drifted toward the southeast relative to the north Atlantic, and the oceanic ridge system has made a succession of small jumps so that active spreading has remained coincident with the plume of hottest, weakest mantle material. These ridge jumps have caused the active spreading to propagate into regions of older crust that have been remelted, forming alkalic and even silicic volcanic rocks deposited unconformably over older tholeiitic basalts. Active spreading occurs along a series of 5–60-mile (8–100 km) long zones of fissures, graben, and dike swarms, with basaltic and rhyolitic volcanoes rising from central parts of fissures. Hydrothermal activity is intense along the fracture zones, with diffuse faulting and volcanic activity merging into a narrow zone within a few kilometers depth beneath the surface. Detailed geophysical studies have shown that magma episodically rises from depth into magma chambers located a few miles (kilometers) below the surface, then dikes intrude the overlying crust and flow horizontally for tens of miles to accommodate crustal extension of several to several tens of feet over several hundred years.

Many Holocene volcanic events are known from Iceland, including 17 eruptions of Hekla from the Southern Volcanic zone. Iceland has an extensive system of glaciers and has experienced a number of eruptions beneath the glaciers that cause water to infiltrate the fracture zones. The mixture of water and magma induces explosive events including Plinian eruption clouds, phreo-magmatic, tephra-producing eruptions, and sudden floods known as jokulhlaups, induced when the glacier experiences rapid melting from contact with magma. Many Icelanders have learned to use the high geothermal gradients to extract geothermal energy for heating, and to enjoy the many hot springs on the island.

YELLOWSTONE HOT SPOT

The northwest corner of Wyoming and adjacent parts of Idaho and Montana were established as Yellowstone National Park in 1872 by President Ulysses S. Grant, and it remains the largest national park in the conterminous United States. The park serves as a large nature preserve and has large populations of moose, bear, sheep, elk, bison, numerous birds, and a diverse flora. The park sits on a large upland plateau resting at about 8,000 feet (2,400 m) elevation straddling the continental divide. The plateau is surrounded by mountains that range from 10,000 to 14,000 feet (3,000–4,250 m) above sea level. Most of the rocks in the park formed from a massive volcanic eruption that occurred 600,000 years ago, forming a collapse caldera 28 miles (45 km) wide and 46 miles (74 km) long. Yellowstone Lake now largely occupies the deepest part of the caldera. The region is still underlain by molten magma that heats the groundwater system, which boasts more than 10,000 hot springs, 200 geysers, and numerous steaming fumaroles, and hot mud pools. The most famous geyser in the park is Old Faithful, which erupts an average of once every 64.5 minutes blowing 11,000 gallons (41,500 L) of water 150 feet (46 m) into the air. The most famous hot springs include Mammoth hot springs, on the northern side of the park, where giant travertine and mineral terraces have formed from the spring, and where simple heat-loving (thermophilic) organisms live in the hot waters. Other remarkable features of the park include the petrified forests buried and preserved by the volcanic ash, numerous volcanic formations including black obsidian cliff, and waterfalls and canyons including the spectacular Lower Falls in the Grand Canyon of the Yellowstone.

The massive eruption from Yellowstone caldera 600,000 years ago covered huge amounts of the western United States with volcanic ash. If such an eruption were to occur today, the results would be devastating, with perhaps 20 percent of the lower United States covered with thick, hardened ash and burning fumes extending across the whole country. There has been some concern recently about an increase in some of the thermal activity in Yellowstone, although it is probably related to normal changes within the complex system of heated groundwater and seasonal or longer changes in the groundwater system. First, Steamboat geyser, which had been quiet for two decades, began erupting in 2002. New lines of fumaroles formed around Nymph Lake, including one line 250 feet long (75 m) that forced the closure of the visitor trail around the geyser basin. Other geysers, have seen temperature increases from 152°F (67°C) to 190°F (88°C) over a several-month period. Other changes include a greater discharge of steam from some geysers, changes in the frequency of eruptions, and a greater turbidity of thermal pools. Perhaps most worrisome is the discovery of a large bulge beneath Yellowstone Lake, although its age and origin are uncertain. Fears are that the bulge may be related to the emplacement of magma to shallow crustal levels, a process that sometimes precedes eruptions. But the bulge was recently discovered because new techniques are being used to map the lake bottom. The feature has an unknown age and may have been there for decades to hundreds of years.

Yellowstone Park is underlain by a hot spot, the surface expression of a mantle plume. As the North American plate has migrated 280 miles (450 km) southwestward with respect to this hot spot in the past 16 million years, the volcanic effects migrated from the Snake River Plain to the Yellowstone Plateau. There is currently a parabolic-shaped area of seismicity, active faulting, and centers of igneous intrusion centered around the parabolic area, all of which are migrating northeastward. Heat and magma from this mantle plume has emplaced as much as 7.5 miles (12 km) of mafic magma into the continental crust over the plume along this trace, causing the surface eruptions of the massive Snake River Plain flood basalts, and the Yellowstone volcanics. On geological timescales massive volcanism and other effects of this hot spot will likely continue and also slowly move northeast.

See also CONVECTION AND THE EARTH'S MANTLE; ENERGY IN THE EARTH SYSTEM; VOLCANO.

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Hubble, Edwin **(1889–1953) American *Astronomer*** Edwin Powell Hubble was born on November 20, 1889, in Marshfield, Missouri, but his family moved to Wheaton, Illinois, the same year. In his career Hubble made two important discoveries that changed scientists' understanding of the universe. He was the first to prove the existence of galaxies beyond the Milky Way, and he discovered that the redshift of galaxies increased with their distance from the Milky

Way, showing that the universe is expanding in all directions.

Hubble performed well in grade and high school but paid more attention to sports than academics. He completed a bachelor of science degree at the University of Chicago in 1910, with concentrations in mathematics, astronomy, and philosophy. From 1910 to 1913 Hubble was a Rhodes Scholar at Oxford, England, where he studied jurisprudence and Spanish, then returned to the United States. He was inducted into the Kentucky bar association though he never practiced law. Instead he taught high school and became a basketball coach, until he served in World War I. After the war Hubble returned to astronomy studies at the Yerkes Observatory at the University of Chicago, earning a Ph.D. in 1917 for his dissertation, "Photographic Investigations of Faint Nebula." In 1919 Hubble took a position at the Mount Wilson Observatory near Pasadena, California, where he was the first person to use Palomar's 200-inch Hale Telescope. Edwin Hubble died suddenly on September 28, 1953, of a cerebral thrombosis.

When Hubble arrived at the Mount Wilson observatory in 1919, astronomers believed that the universe did not extend beyond the Milky Way, but Hubble soon made discoveries that dramatically expanded the known universe. Using the 100-inch (254-cm) Hooker Telescope (then the largest telescope in the world) Hubble identified a new type of star, a Cepheid variable, that varied in luminosity with a specific period correlated with the luminosity. On January 1, 1925, Hubble announced a correlation between the distance of these objects and their period/luminosity, showing that they were located at very distant places beyond the Milky Way Galaxy. This discovery fundamentally changed the way astronomers viewed the universe.

Hubble next spent time examining the redshift of distant galaxies. Redshifts of the electromagnetic spectrum occur when the emitted or reflected light from an object is shifted toward the less energetic (red) end of the electromagnetic spectrum by the Doppler effect. This happens for objects moving away from the observer, since the radiation needs to travel a greater distance and increases its wavelength as the object moves away from the observer. Conversely, blueshifts occur when an object is moving toward the observer and the wavelengths of radiation from the object are compressed into a smaller area, causing the wavelength to decrease. Redshift was known for some time, with general knowledge that larger redshifts meant that objects were moving away faster from the observer. Hubble and his colleague Milton Humason plotted the redshifts of 46 distant objects against their distance from Earth and found a rough proportionality with increasing redshifts with distance. They found a proportionality constant to explain this correlation and stated that the farther the object or galaxy is located from Earth, the faster it is moving away—a statement that later became known as Hubble's law. The current estimate of the constant of proportionality for Hubble's Law is 70.1 +/- 1.3 km/sec/Megaparsec, although Hubble initially estimated it to be higher. The redshift means that the more distant the galaxies, the faster they are moving away from Earth and from one another. This was found to agree with Albert Einstein's equations of general relativity and supported his ideas for a homogeneous isotropic expanding universe. Interestingly, when Einstein formulated his laws of general relativity in 1917, he did not know about the redshift and Hubble's law, so he introduced a cosmological constant (a "fudge factor") into his equations to counter the result that his calculations showed the universe must be expanding. When Hubble announced his results, Einstein retracted his cosmological constant, calling it the biggest blunder of his life, then his calculations agreed with Hubble's observations. Hubble's law is now commonly stated as "the greater the distance between any two galaxies, the greater their speed of separation." Hubble's law is one of the major observations that supports the idea that the universe was created in a big bang, and that all matter is moving away from other matter in a homogenous, isotropically expanding universe.

See also ASTRONOMY; GALAXIES; ORIGIN AND EVOLUTION OF THE UNIVERSE; UNIVERSE.

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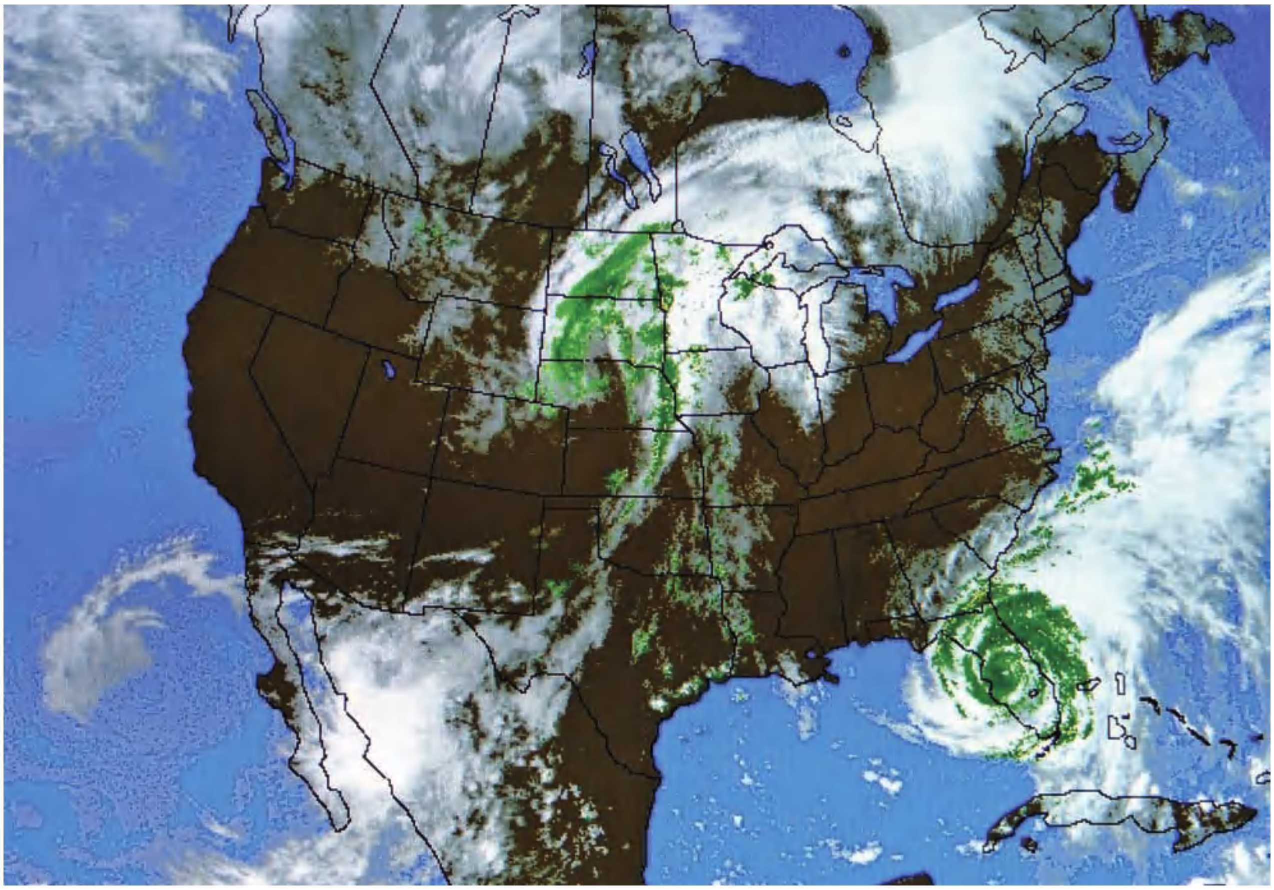
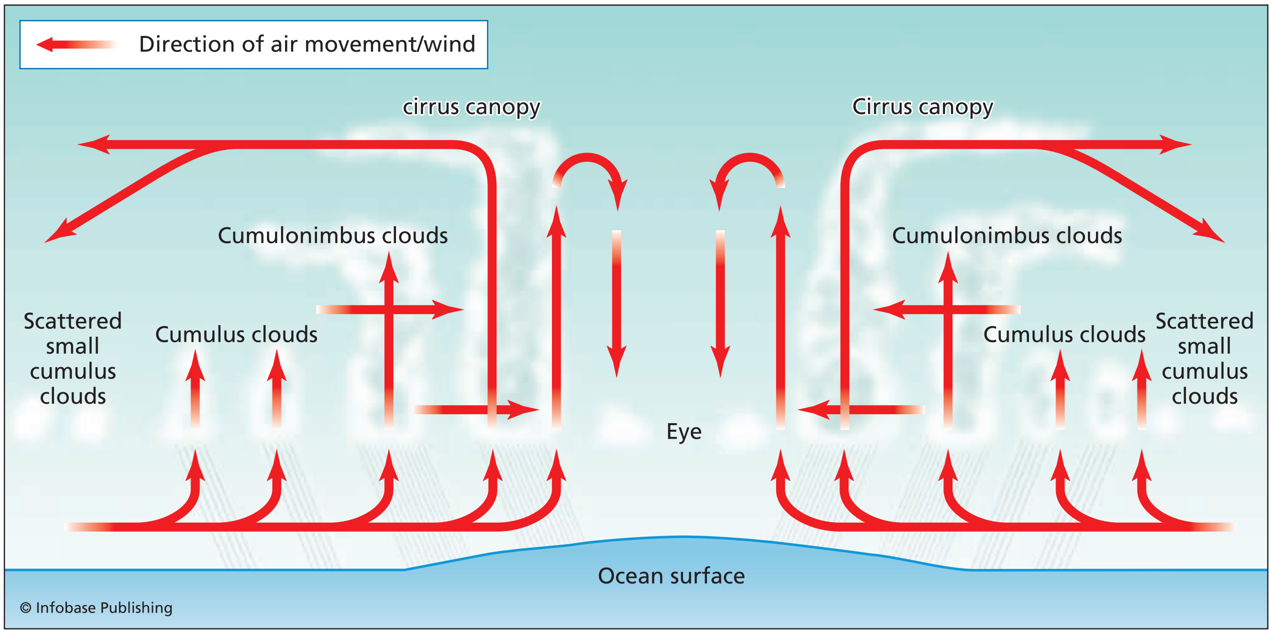
hurricane Intense tropical storms with sustained winds of more than 74 miles per hour (119 km/hr) are known as hurricanes if they form in the northern Atlantic or eastern Pacific Oceans, cyclones if they form in the Indian Ocean near Australia, or typhoons if they form in the western North Atlantic Ocean. Most large hurricanes have a central eye with calm or light winds and clear skies or broken clouds, surrounded by an eye wall, a ring of very tall and intense thunderstorms that spin around the eye, with some of the most intense winds and rain of the entire storm system. The eye is surrounded by spiral rain bands that spin counterclockwise in the Northern Hemisphere (clockwise in the Southern Hemisphere) in toward the eye wall, moving faster and generating huge waves as they approach the center. Wind speeds increase toward the center of the storm, and the atmospheric pressure decreases to a low in the eye, uplifting the sea surface in the storm center. Surface air flows in toward the eye of the hurricane, then moves upward, often above nine miles (15 km), along the eye wall. From there it moves outward in a large outflow, until it descends outside the spiral rain bands. Air in the rain bands is ascending, whereas between the rain bands belts of descending air counter this flow. Air in the very center of the eye descends to the surface. Hurricanes drop enormous amounts of precipitation, typically spawn numerous tornadoes, and cause intense coastal damage from winds, waves, and storm surges, where the sea surface may be elevated 10 to 30 feet (3–10 m) above its normal level.

Most hurricanes form in summer and early fall over warm tropical waters when winds are light and the humidity is high. In the North Atlantic hurricane season generally runs from June through November, when the tropical surface waters are warmer than 80°F (26.5°C). They typically begin when a trigger acts on a group of unorganized thunderstorms, causing the air to begin converging and spinning. These triggers are found in the intertropical convergence zone that separates the northeast trade winds in the Northern Hemisphere from the southeast trade winds in the Southern Hemisphere. Most hurricanes form within this zone, between 5° and 20° latitude. When a low-pressure system develops in this zone during hurricane season, the isolated thunderstorms can develop into an organized convective system that strengthens to form a hurricane. Many Atlantic hurricanes form in a zone of weak convergence on the eastern side of tropical waves that form over North Africa, then move westward, where they intensify over warm tropical waters.

For hurricanes to develop, high-level winds must be mild, otherwise they might disperse the tops of the growing thunderclouds. In addition high-level winds must not be descending, since this would also inhibit the upward growth of the thunderstorms. Once the



Hurricane Frances over Florida, September 5, 2004 *(Carolina K. Smith, M.D., Shutterstock, Inc.)*



Cross section of typical hurricane showing eye, eye wall, and circulating spiral bands of cumulonimbus clouds

mass of thunderstorms is organized, hurricanes gain energy by evaporating water from the warm tropical oceans. When the water vapor condenses inside the thunderclouds, this heat energy is then converted to wind energy. The upper-level clouds then move outward, causing the storm to grow stronger and decreasing the pressure in the storm's center. The low pressure in the center draws the outlying thunderstorms in toward the surface low, and these rain bands then spiral inward because of the Coriolis force. The clouds spin progressively faster as they move inward, owing to the law of conservation of angular momentum.

The Saffir-Simpson scale classifies the strength of hurricanes by measuring the damage potential of a storm, considering factors such as the central barometric pressure, maximum sustained wind speeds, and potential height of the storm surge.

- Category 1 hurricanes have central pressures greater than 980 millibars, sustained winds between 74 and 95 miles per hour (119–153 km/hr), and a likely 4–5 foot (1–1.5 m) storm surge. Damage potential is minimal, with likely effects including downed power lines, ruined crops, and minor damage to weak buildings.
- Category 2 hurricanes have central barometric pressures between 979 and 965 millibars, maximum sustained winds between 96 and 110 miles per hour (155–177 km/hr), and 6–8 foot (1.8–2.4 m) storm surges. Damage is typically moderate, including roof and chimney destruction, beached and splintered boats, destroyed crops, road signs, and traffic lights.
- Category 3 hurricanes have central barometric pressures falling between 964 and 945 millibars, sustained winds between 111 and 130 miles per hour (179–209 km/hr), and storm surges between nine and 12 feet (2.7–3.6 m). Category 3 hurricanes are major storms capable of extensive property damage including uprooting large trees, destroying mobile homes, and demolishing poorly constucted coastal houses. For comparison, Hurricane Katrina was a category 3 storm when it struck New Orleans in 2005.
- Category 4 storms can be devastating, with central barometric pressures falling between 940 and 920 millibars, sustained winds between 131 and 155 miles per hour (211–249 km/hr), and storm surges between 13 and 18 feet (4–5.5 m). These storms typically rip the roofs off homes and businesses, destroy piers, and throw boats well inland. Waves may breach sea walls causing large-scale coastal flooding.
- Category 5 storms are massive, with central barometric pressures dropping below 920 millibars, maximum sustained winds above 155 miles per hour (249 km/hr), and storm surges of more than 18 feet (5.5 m). Storms with this power rarely hit land, but when

they do they can level entire towns, moving large amounts of coastal sediments, and causing large death tolls.

Hurricanes inflict some of the most rapid and severe damage and destruction to coastal regions, and can cause numerous deaths. The number of deaths from hurricanes has been reduced dramatically in recent years owing to an increased ability to forecast the strength and landfall of hurricanes, and the ability to monitor their progress with satellites. The cost of hurricanes in terms of property damage has greatly increased, however, as more and more people build expensive homes along the coast. The greatest number of deaths from hurricanes has been from storm surges. Storm surges typically come ashore as a wall of water that rushes onto land at the forward velocity of the hurricane, as the storm waves on top of the surge are pounding the coastal area with additional energy. For instance, when Hurricane Camille hit Mississippi in 1969 with 200-mile-per-hour winds (322 km/hr), a 24-foot (7.3-m) high storm surge moved into coastal areas, killing most of the 256 who perished in this storm. Winds and tornadoes account for more deaths. Heavy rains from hurricanes also cause considerable damage. Flooding and severe erosion is often accompanied by massive mudflows and debris avalanches, such as those caused by Hurricane Mitch in Central America in 1998. In a period of several days Mitch dropped 25 to 75 inches (63.5–190.5 cm) of rain on Nicaragua and Honduras, initiating many mudslides that were the main cause of the more than 11,000 deaths from this single storm. One of the worst events was the filling and collapse of a caldera on Casitas volcano. When the caldera could hold no more water, it gave way, sending mudflows (lahars) cascading down on several villages and killing 2,000.

Storm surges are water pushed ahead of storms and moving typically on to land as exceptionally high tides in front of severe ocean storms such as hurricanes. Storms and storm surges can cause some of the most dramatic and rapid changes in the coastal zones and are one of the major, most unpredictable hazards to those living along coastlines. Storms that produce surges include hurricanes (which form in late summer and fall) and extratropical lows (which form in late fall through spring). Hurricanes originate in the Tropics and (for North America) migrate westward and northwestward before turning back to the northeast to return to the cold North Atlantic, weakening the storm. North Atlantic hurricanes are driven to the west by the trade winds and bend to the right because the Coriolis force makes objects moving above Earth's surface appear to curve to the right in the Northern Hemisphere. Other weather conditions further modify hurricane paths, such as the location of high- and low-pressure systems and their interaction with weather fronts. Extratropical lows (also known as coastal storms, and northeasters) move eastward across North America and typically intensify when they hit the Atlantic and move up the coast. Both types of storms rotate counterclockwise, and the low pressure at storm center raises the water up to several tens of feet. This extra water moves ahead of the storms as a storm surge that is an additional height of water above the normal tidal range. The wind from the storms adds further height to the storm surge, with the total height of the surge being determined by the length, duration, and direction of wind, plus how low the pressure becomes in the center of the storm. The most destructive storm surges are those that strike low-lying communities at high tide, as the effects of the storm surge and the regular astronomical tides are cumulative. Add high winds and large waves to the storm surge and coastal storms and hurricanes are masters of disaster, as well as powerful agents of erosion. They can remove entire beaches and rows of homes, causing extensive cliff erosion and, significantly, redistributing sands in dunes and the back beach environment. Precise prediction of the height and timing of the approach of the storm surge is necessary to warn coastal residents when they need to evacuate and leave their homes.

Like many natural catastrophic events, the heights of storm surges to strike a coastline are statistically predictable. If the height of the storm surge is plotted on a semilogarithmic plot, with the height plotted in a linear interval and the frequency (in years) plotted on a logarithmic scale, then a linear slope results. This means that communities can plan for storm surges of certain height to occur once every 50, 100, 300, or 500 years, although there is no way to predict when the actual storm surges will occur. One must remember, however, that this is a long-term statistical average, and that one, two, three, or more 500-year events may occur over a relatively short period, but averaged over a long time, the events average out to once every 500 years.

EXTRATROPICAL CYCLONES

Extratropical cyclones, also known as wave cyclones, are hurricane-strength storms that form in middle and high latitudes at all times of the year. Examples of these strong storms include the famous northeasters of New England, storms along the east slopes of the Rockies and in the Gulf of Mexico, and smaller hurricane-strength storms that form in arctic regions. These storms develop along polar fronts that form semicontinuous boundaries between cold polar air and warm subtropical air. Troughs of low pressure

DO BAY OF BENGAL CYCLONES HAVE TO BE SO DEADLY?

Officials estimate that more than 100,000 people perished from tropical cyclone Nargis that hit Myanmar on May 2, 2008. Ninety-five percent of buildings in the coastal region were destroyed by the 12-foot (3.7-m) high storm surge, and more than a million were made homeless and without access to electricity, clean water, or medical care for many months following the disaster. When Cyclone Nargis blew into coastal Myanmar on May 2, it was unfortunately not the first time in recent years that a cyclone has extracted a huge toll on the generally poor, coastal residents of the region.

Bangladesh and the recently devastated coastal Myanmar are densely populated, low-lying regions mostly at or near sea level at the head of the Bay of Bengal. They are delta environments, built where the Ganges, Brahmaputra, and Irrawaddy Rivers drop their sediment eroded from the Himalaya Mountains. These areas sit directly in the path of many Bay of Bengal tropical cyclones (another name for a hurricane), and have been hit by seven of the 10 deadliest hurricane disasters in recorded history.

On November 12 and 13, 1970, a category 3 storm known as the Bhola cyclone hit Bangladesh with 115 mph (184 kph) winds, and a 23-foot (7-m) high storm surge that struck at the astronomically high tides of a full moon. The devastating result caused 500,000 human deaths and half a million farm animals perished. The death toll is hard to estimate in this rural region, with estimates ranging from 300,000 to 1 million people lost in this one storm alone. Most perished from flooding associated with the storm surge that covered most of the deltaic islands on the Ganges River. Again in 1990 another cyclone hit the same area, this time with a 20-foot (6-m) storm surge and 145-mile-per-hour (232 km/hr) winds, killing another 140,000 people and another half-million farm animals. In November 2007 Bangladesh was hit by a powerful category 5 cyclone, with 150 mph (240 km/hr) winds, and was inundated with a 20-foot (6-m) high storm surge. Since the 1990 storm, the area had a better warning system in place, so many more people evacuated low-lying areas before the storm. Still, it is estimated that 5,000–10,000 people perished during Typhoon Sidr, most from the effects of the storm surge.

Why do so many continue to move to areas prone to repeated strikes by tropical cyclones? Bangladesh and coastal Myanmar are overpopulated regions with densities 50 times as great as that of farmlands typical of the midwestern United States. Bangladesh's per capita income is only $200, whereas Myanmar's is $1,900. The delta regions of Bangladesh and Myanmar are the respective country's most fertile. Farmers can expect to yield three rice crops per year, making them attractive place to live despite the risk of storm surges. With the continued population explosion in coastal regions of the Bay of Bengal and the paucity of fertile soils in higher grounds, the delta regions continue to be farmed by millions and continue to be hit by tropical cyclones like the 1970, 1990, 2007, and 2008 disasters. The lower death toll in the 2007 category 5 cyclone in Bangladesh compared with similar earlier storms demonstrates that investment in better warning systems and planned evacuations can save tens to hundreds of thousands of lives. The government of Myanmar has not opened itself to international aid, advice on emergency planning, and better protection of its population.

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can develop along these polar fronts, and winds that blow in opposite directions to the north and south of the low set up a cyclonic (counterclockwise in the Northern Hemisphere) wind shear that can cause a wavelike kink to develop in the front. This kink, an incipient cyclone, includes (in the Northern Hemisphere) a cold front that pushes southward and counterclockwise and a warm front that spins counterclockwise and moves to the north. A comma-shaped band of precipitation develops around a central low that develops where the cold and warm fronts meet, and the whole system will migrate east or northeast along the polar front, driven by high-altitude steering winds.

The energy for extratropical cyclones to develop and intensify comes from warm air rising and cold air sinking, transforming potential energy into kinetic energy. Condensation also provides extra energy as latent heat. These storms can intensify rapidly and are especially strong when the cold front overtakes the warm front, occluding the system. The point at which the cold front, warm front, and occluded front meet is known as a triple point. It is often the site of the formation of a new secondary low-pressure system to the east or southeast of the main front. This new secondary low often develops into a new cyclonic system and moves eastward or northeastward, and may become the stronger of the two lows. In the case of New England's northeasters, the secondary lows typically develop off the coast of the Carolinas or Virginia, then rapidly intensify as they move up the coast, bringing cyclonic winds and moisture in from the northeast off the Atlantic Ocean.

POLAR LOW

Polar lows are hurricane- or gale-strength storms that form over water behind (poleward) the main polar front. They can form over either the Northern or Southern Hemisphere oceans but are a larger menace to the more populated regions around the North Atlantic, North Sea, and Pacific Ocean, as well as the Arctic Ocean. Most polar lows are much smaller than tropical and midlatitude cyclones, with diameters typically fewer than 600 miles (1,000 km). Like hurricanes, many polar lows have spiral bands of precipitation (snow in this case) that circle a central warmer low-pressure eye, whereas other polar lows develop a comma-shaped system.

Most polar lows develop during winter months. In the Northern Hemisphere they form along an arctic front, where frigid air blows off landmasses and encounters relatively warm current–fed ocean water, producing a rising column of warm air and sinking columns of cold air. This situation sets up an instability that induces condensation of water vapor in the rising air, along with the associated release of latent heat that then warms the atmosphere. The warming lowers the surface pressure, adding convective updrafts to the system and starting the classical spiral cloud band formation. Polar lows can attain central barometric pressures comparable to hurricanes (28.9 inches or 980 mbars) but tend to dissipate more quickly when they move over the cold polar landmasses.

Storms can open new tidal inlets where none previously existed (without regard to whether any homes were present in the path of the new tidal inlet) and can close inlets previously in existence. Storms also tend to remove large amounts of sand from the beach face and redeposit it in the deeper water offshore (below wave base), but this sand tends gradually to move back onto the beach in the intervals between storms when the waves are smaller. In short, storms are extremely effective modifiers of the beach environment, although they are unpredictable and dangerous.

Many cyclones are spawned in the Indian Ocean. Bangladesh is a densely populated, low-lying country mostly at or near sea level between India and Myanmar. A delta environment, built where the Ganges and Brahmaputra Rivers drop their sediment eroded from the Himalaya Mountains, Bangladesh sits directly in the path of many Bay of Bengal tropical cyclones and has been hit by seven of the nine most deadly hurricane disasters in recorded history. On November 12 and 13, 1970, a category 5 typhoon hit Bangladesh with 155-mile-per-hour (249.5 km/hr) winds and a 23-foot (7-m) high storm surge that struck at the astronomically high tides of a full moon. The result was devastating; 500,000 human deaths and half a million farm animals dead. Again in 1990, another cyclone hit the same area, this time with a 20-foot (6-m) storm surge and 145-mile-per-hour (233 km/hr) winds, killing another 140,000 people and another half-million farm animals.

HURRICANE KATRINA AND THE CONTINUED THREAT TO NEW ORLEANS

On August 28 and early September, 2005, Hurricanes Katrina and Rita devastated the Gulf Coast, inundating New Orleans with up to 20 feet (6 m) of water. While the storm reached category 5 strength offshore, it struck as a category 3, sparing the region the worst potential damage. More than 1,050 were killed in New Orleans alone, however, and large sections of the Gulf Coast in Louisiana, Mississippi, Alabama, and Florida were devastated, with hundreds more dead in these areas. Large sections of the city and coastal regions are now uninhabitable, having been destroyed by floods and subsequent decay by contaminated water and toxic mold. Damage estimates and costs of rebuilding are astronomical, some reaching $300 billion, making the Katrina/Rita disaster the costliest in U.S. history.

One of the initial responses from the residents of the Gulf Coast and much of the rest of the nation was to vow to rebuild the city grander and greater than before. This scientifically unsound response could lead to even greater human catastrophes and financial loss in the future. New Orleans sits on a coastal delta in a basin that is up to 10 feet (3 m) below sea level and is sinking at rates of one-third of an inch to two inches (1–5 cm) per year. Much of the city could be eight feet (2–3 m) farther below sea level by the end of the century. As New Orleans continues to sink, 17.5-foot (5-m) tall levees built to keep the gulf and Lake Pontchartrain out of the city have to be raised repeatedly, and the higher they are built, the greater the likelihood of failure and catastrophe.

Eighteen-foot (5-m) tall flood-protection levees built along the Mississippi keep the river level about 14 feet (4 m) above sea level at New Orleans. If these levees were breached, water from the river would quickly fill in the 10-foot (3-m) deep depression with 25 feet (7–8 m) of water and leave a path of destruction where the torrents of water would rage through the city. These levees also channel the sediments that would naturally get deposited on the floodplain and delta far out into the Gulf of Mexico, with the result that the land surface of the delta south of New Orleans has been sinking below sea level at an alarming rate. A total land area the size of Manhattan disappears every year; this means New Orleans will be directly on the gulf by the end of the century. Current assessments of damage from Katrina are alarming and push that estimate forward by years.

The projected setting of the city in 2100 is in a hole up to 18 feet (5–6 m) below sea level, directly on the hurricane-prone coast, and south of Lake Pontchartrain (by then part of the gulf). The city will need to be surrounded by 50- to 100-foot (15–30-m) tall levees that will make it look like a fish tank submerged off the coast. The levee system will not be able to protect the city from hurricanes any stronger than Katrina. Hurricane storm surges and tsunamis could easily initiate catastrophic collapse of any levee system, causing a major disaster. Advocates of rebuilding are suggesting elevating buildings on stilts or platforms, but they forget that the city will be 10–20 feet (3–6 m) feet below sea level by 2090 and that storm surges may be 30 feet (10 m) above sea level. A levee failure in this situation would be catastrophic, with a debris-laden 50-foot (15-m) tall wall of water sweeping through the city at 30 miles per hour (50 km/hr), hitting these proposed buildings-on-stilts with the force of Niagara Falls and causing devastation equivalent to an Indian Ocean tsunami.

Sea-level rise is rapidly becoming a major global hazard with which we must contend, since most of the world's population lives near the coast in the reach of the rising waters. The current rate of rise of an inch every 10 years will have enormous consequences. Many of the world's large cities, including New York, Houston, New Orleans, and Washington, D.C., are located within a few feet (1 m) of sea level. If sea levels rise a few feet (1 m), many of the city streets will be underwater, not to mention basements, subway lines, and other underground facilities. New Orleans will be the first to go under, lying a remarkable 10–20 feet (3–6 m) below projected sea level, on the coast, at the turn of the next century. These sobering facts suggest that government and private planners should not rebuild major coastal cities in 15-foot (5-m) deep holes along the sinking, hurricane-prone coast. Governments, planners, and scientists must make more sophisticated plans to protect against rising sea levels. The first step would be to use reconstruction money for rebuilding New Orleans as a bigger, better, stronger city in a location where it is above sea level and will last for more than a couple of decades, saving the lives and livelihoods of hundreds of thousands of people.

HURRICANE ANDREW, 1992

Hurricane Andrew was the second-most destructive hurricane in U.S. history, causing more than $30 billion in damage in August 1992. Andrew began to form over North Africa and grew in strength as trade winds drove it across the Atlantic. On August 22 Andrew had grown to hurricane strength and moved across the Bahamas with 150-mile-per-hour (241 km/hr) winds, killing four people. On August 24 Andrew smashed into southern Florida with a nearly 17-foot (5.2-m) high storm surge, steady winds of 145 miles per hour (233 km/hr), and gusts up to 200 miles per hour (322 km/hr). Andrew's path traversed a part of south Florida that had hundreds of thousands of poorly constructed homes and trailer parks, and hurricane winds caused intense and widespread destruction. Andrew destroyed 80,000 buildings, severely damaged another 55,000, and demolished thousands of cars, signs, and trees. In southern Florida 33 people died. Andrew lost much of its strength as it traveled across Florida, but it later moved back into the warm waters of the Gulf of Mexico and regained much of that strength. On August 26 Andrew made landfall again, this time in Louisiana, with 120-mile-per-hour (193-km/hr) winds, where it killed another 15 people. Andrew's winds stirred up the fish-rich marshes of southern Louisiana, where the muddied waters were agitated so much that the decaying organic material overwhelmed the oxygen-rich surface layers, suffocating millions of fish. Andrew then continued to lose strength but dumped flooding rains over much of Mississippi.

THE 1900 GALVESTON HURRICANE

The deadliest natural disaster to affect the United States was a category 4 hurricane that hit Galveston Island, Texas, on September 8, 1900. Galveston is a low-lying barrier island south of Houston, and in 1900 it was a wealthy port city. Residents of coastal Texas received early warning of an approaching hurricane from a Cuban meteorologist, but most people ignored this advice. Later, perhaps too late, U.S. forecasters warned of an approaching hurricane, and many people then evacuated the island to relative safety inland. But many others remained on the island. In the late afternoon the hurricane moved into Galveston, and the storm surge hit at high tide, covering the entire island with water. Even the highest point on the island was covered with one foot (255 cm) of water. Winds of 120 miles per hour (190 km/hr) destroyed wooden buildings as well as many of the stronger brick buildings. Debris from destroyed buildings crashed into other structures, demolishing them and creating a moving mangled mess for residents trapped on the island. The storm continued through the night, battering the island and city with 30-foot (9-m) high waves. In the morning residents who found shelter emerged to see half of the city totally destroyed, and the other half severely damaged. But worst of all, thousands of bodies were strewn everywhere—6,000 on Galveston Island and another 1,500 on the mainland. With no way off the island (all boats and bridges were destroyed), survivors faced the additional danger of disease from the decaying bodies. When help arrived from the mainland, the survivors needed to dispose of the bodies before cholera set in, so they put the decaying corpses on barges and dumped them at sea. But the tides and waves soon brought the bodies back, and they eventually had to be burned in giant funeral pyres built from wood from the destroyed city. Galveston was rebuilt with a seawall made of stones to protect the city; however, in 1915 another hurricane struck Galveston, claiming 275 additional lives.

The Galveston seawall has since been reconstructed and is higher and stronger, although some forecasters believe that even this seawall will not be able to protect the city from a category 5 hurricane. The possibility of a surprise storm hitting Galveston again is not so remote, as demonstrated by the surprise tropical storm of early June 2001. Weather forecasters did not successfully predict the rapid strengthening and movement of this storm, which dumped 23–48 inches (58–122 cm) of rain on different parts of the Galveston-Houston area and attacked the seawall and coastal structures with huge waves and 30-mile-per-hour (48-km/hr) winds. Twenty-two died in the area from the surprise storm, showing that even modern weather forecasting cannot always adequately predict tropical storms. It is best to heed early warnings and prepare for rapidly changing conditions when hurricanes and tropical storms approach vulnerable areas.

See also ATMOSPHERE; BEACHES AND SHORELINES; CLOUDS; GEOLOGICAL HAZARDS.

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Hutton, James (1726–1797) Scottish *Geologist*

James Hutton was a major 18th-century theorist who studied the Earth and the processes by which it was shaped. He proposed a system for shaping the surface of the Earth. He believed the chief agent for major geological changes was heat generated deep underneath the planet's crust. Proponents of Hutton's theory of the Earth were called vulcanists, after Vulcan, the Roman god of fire, owing to the emphasis of his system on the action of heat and volcanoes, or plutonists, after the ruler of the underworld, Pluto. His proposal of a continuously acting cyclical system of degradation of the land into sediment deposited into strata under the sea, followed by upheaval from volcanic activity, led to decades of debate.

James Hutton's most important contribution to science was his book *Theory of the Earth*. The theory was simple yet contained such fundamental ideas that he was later known as the founder of modern geology. In the 30-year period when he was developing and writing his ideas, other areas of earth sciences had been explored. However, geology had not really been recognized as an important science. Hutton's *Theory of the Earth* contained three main ideas:

- estimating the amount of time the Earth had existed as a "habitable world"
- determining the changes it had undergone in the past
- speculating on whether any end to the present state of affairs could be foreseen

He also talked about how rocks were good indications of the different periods and how they could tell geologists roughly when the Earth was formed. Initially his ideas were not well received by his fellow scientists, because they contradicted the natural conservatism of many geologists, including a reluctance to abandon belief in the biblical account of creation and the widespread catastrophism. By the 1830s, even though geologists were still conservative, they were better equipped to assess the value of Hutton's theory.

CHILDHOOD AND COLLEGE

James Hutton was born in Edinburgh, Scotland, on June 3, 1726, the son of William Hutton and Sarah

Balfour. William died when James was only three, leaving an inheritance that was sufficient for Sarah to raise James and his three sisters, and to send James to the University of Edinburgh when he was 14 years old. While in college James studied humanities but became interested in chemistry when a professor performed an experiment demonstrating that a single acid could dissolve inferior metals, but that two acids were necessary to dissolve gold.

Despite demonstrating academic potential and natural intellectual curiosity, James began an apprenticeship in a lawyer's office when he was 17 years old, but it was obvious that his interests lay elsewhere. His boss released him from their agreement. Because coursework in medicine offered the best opportunity to learn chemistry, Hutton enrolled in medical school at the University of Edinburgh. After three years he moved to Paris to study anatomy. In 1749 he was awarded a doctor of medicine degree after transferring to Leiden, the Netherlands, but he was not interested in practicing medicine.

GEOLOGICAL AND AGRICULTURAL STUDIES

Hutton toured a little, and his interest in chemistry grew into a love of geology and mineralogy. Between 1752 and 1753 he lived with a farmer in Norfolk, England, where he was fascinated by the rows of black flints embedded in the white chalk. He spent time gazing at heaps of seashells on the east coast and noticed chalk and foreign stones embedded in cliffs to the north. In the west he observed red-colored chalk in the strata. With such geological variety above ground, he wondered what was underneath the ground.

Hutton also gained practical knowledge of agriculture during his travels. After spending two years on a farm in Norfolk, he stopped by Flanders to compare animal husbandry techniques with what he learned in England. In 1754 he decided to cultivate farmland in Berwickshire that his father had left him. For 14 years Hutton farmed and applied scientific principles to improve crop yields. While farming he became captivated with the fate of the soil. Over time the soil was washed away, ending up in streams that eventually channeled into the oceans. He must have wondered why this process did not result in a completely flat Earth over long periods of time. He was successful not only in his farming but in a business venture manufacturing ammonium chloride from soot, a process he had helped to devise with a friend. In 1768, with his finances secure, he leased his farmlands and moved to Edinburgh, where he could spend more time studying science.

While in Edinburgh he made many friends among scientific acquaintances including the chemist Joseph Black, who discovered fixed air (carbon dioxide) and the economist Adam Smith. These three founded the Oyster Club, a small society that met weekly to discuss various issues over dinner and to go on field trips. The affable environment afforded frequent scholarly discussions, and Hutton read voraciously on all matters of science. Enjoyable promenades opened his eyes to the idea that the lands on which he walked were not as they had always been. He also joined a society that became the Royal Society of Edinburgh in 1783. A deepening interest in geology sent him all over Scotland, England, and Wales study the rocks, the strata, and the landscapes, searching for clues to the Earth's history. He made observations and collected data, formulating a theory that changed the course of geological science.

"THEORY OF THE EARTH"

On March 7, 1785, Hutton was to read his paper, "Theory of the Earth; or an Investigation of the Laws Observable in the Composition, Dissolution, and Restoration of Land upon the Globe" to the newly chartered Royal Society of Edinburgh. But he became overly nervous from anticipation and the task fell to his friend Joseph Black. He had recovered by the next meeting on April 4, when he read the remainder of his paper.

At the time the prevailing theory for the Earth's formation emphasized the importance of water. The German geologist Abraham Gottlob Werner piloted this group of neptunists, who believed that the Earth's surface was formed by sedimentary deposition in a great turbulent ocean. Of course, many believed this great ocean was the result of a giant flood as described in the biblical book of Genesis. Literal interpretation of the Bible led many to accept the age of the Earth as approximately 6,000 years. Hutton did not think this corresponded with the evidence he had observed.

In a stroke of genius Hutton resolved that the history of the Earth must be explained by events of the present. In other words the natural processes observed today were the same processes that sculpted the Earth's surface into its current form. He thought the Earth was constantly but slowly changing, and that the changes still were occurring. Events such as volcanic eruptions, weathering, and erosion must have had tremendous effects over long periods of time. Hutton was a deist; he believed that nature itself provided evidence of wisdom and design, but after creation, God did not assume control over it. Because Hutton did not believe in a literal interpretation of the Bible, his thinking was not confined to a 6,000-year time frame. In fact, such a short time frame would not allow for the completion of the indeterminate number of cycles, the occurrence of which he had seen evidence. He imagined a much older Earth and postulated that the natural shaping processes of degradation and upheaval were timeless.

This offended many scientists, but Hutton was not just randomly brainstorming or trying to stir up controversy. He based his conclusions on years of careful observation, from which his theory logically germinated. After formulating a hypothesis, Hutton tried to predict what would be observed if the hypothesis were true. Then he roamed the land in search of evidence.

THE EFFECT OF NATURAL PROCESSES ON THE SHAPE OF THE EARTH

Hutton noticed that rocks consisted of strata, parallel orderly layers of consolidated sediment. The layers were composed of different materials that must have been derived from rocks even older than themselves. He thought this was similar to what was currently happening on the ocean floor, where a new layer of sediment was forming. This new layer of sediment contained bits and pieces of material that had been worn away from the land of some preexisting continent and carried out to sea by the natural flowing of waters. Hutton believed the subterranean heat emanating from the interior of the Earth transformed these layers into solid structures. He was aware of the roles that pressure also played, the compaction from upper layers, and the prevention of volatile substances from escaping. Thus the layers of sediment became consolidated after being compacted and cooked for long periods of time.

How could this mechanism account for the formation of mountains? If strata were formed under the sea, what about landmasses that existed thousands of feet above sea level? Hutton again believed that some force underneath the surface of the Earth was responsible. He witnessed powerful volcanic eruptions that he thought were the result of great expansion of the burning igneous matter in the interior of the Earth. He proposed that these great expansions also occurred in the geological past. They caused convulsions that ripped up through the ground and forced rock and crust upward, causing bending and folding, forming mountains and hills. Magma that had not penetrated the Earth's surface during volcanic activity cooled and solidified, forming granite or other crystalline rocks. This in itself was a novel proposition, since at the time the existence of igneous rocks as a type of rock completely separate from sedimentary rock was not recognized. If this were all true, then he predicted that arrangements should exist in the strata such that some upturned strata would be vertical or tilted relative to undisturbed layers. One would expect the slanted strata to have been eroded, and then eventually be overlaid by a new layer of horizontal sedimentary rock. Such structures, called unconformities, are quite prevalent. One famous locality, called Hutton's Unconformity, was located near his home in Berwickshire, along the west coast at Siccar Point.

Erosion played a key role in Hutton's theory of how the Earth was sculpted. Dry land decayed unremittingly. Flowing water and pounding waves ate away at rock beds. Wind and weathering acted on exposed surfaces of mountains, producing new soils. Glaciers broke loose and transported chunks of rocky matter with them. Loose soil containing mineral components and organic matter was washed away by rain, and silt was carried by rivers. Chemical reactions in water caused particulate matter to precipitate out of solution. Eventually all of the loose particulate matter made its way to the oceans, where the sediment settled and was compacted to form new layers of strata, completing the geological cycle.

Hutton was the first to recognize that many igneous rocks were younger than the rocks in which they were found. Veins of unstratified rock-filling fractures were described from many locations. Hutton had predicted these would occur if the granite in these veins was once melted, and that during the forceful convulsions it was pushed up and outward into cracks that resulted from the violent tremors. The problem with this idea was that no one understood the origin or composition of granite.

OPPOSITION

The neptunists repudiated everything Hutton claimed. They argued that melted rocks cooled into glassy rather than crystalline forms. But, substances that precipitated out of aqueous solutions would form crystals. The action of intense heat on stones such as limestone would cause decomposition before being allowed to cool. Regarding the formation of mountains, neptunists also proposed that sedimentary layers were formed under water, but that the ocean was formerly much deeper. Sometimes particulate matter was deposited in a vertical manner, forming peaks under the water. Then the water subsided, the neptunists said, leaving peaks behind as the water level decreased. Neptunists explained veins of unstratified rocks as cracks into which aqueous material containing mineral deposits trickled down. The material hardened over time and left behind the observed intrusions.

When Hutton first presented these ideas, he also published an awkwardly written, anonymous, 30-page pamphlet, "Abstract of a Dissertation . . . Concerning the System of the Earth, Its Duration, and Stability," summarizing his conclusions. As monumental as Hutton's notions were, they seemed to go largely unnoticed. Those who did notice found them complicated. Opposition not only came from neptunists but from catastrophists, who believed that periodic earth-shattering events, not slow-working incessant forces, were responsible for creating geological structures. Three years after his initial presentation in Edinburgh, "Theory of the Earth" was published in the first volume of *Transactions of the Royal Society of Edinburgh* (1788).

The Irish chemist Richard Kirwan published an attack on Hutton's theory in 1793. Kirwan was the president of the Royal Irish Academy and a staunch Werner devotee. He attacked Hutton's works from religious and scientific standpoints. Scientifically he refuted the significance of erosion, the importance of heat in consolidation of sediment, and the idea that granite could crystallize from a melt. Hutton felt his ideas were misrepresented in Kirwan's account.

This printed assault induced Hutton finally to write a full account of his theory for the formation of the Earth with fuller explanations than he had included in the paper published by the Royal Society. In 1795 Hutton published a 1,204-page, two-volume text, *Theory of the Earth with Proofs and Illustrations*. A 267-page third volume was found and published by the Geological Society in 1899, more than 100 years after Hutton's death.

After 1791 Hutton was frequently ill with a kidney and bladder ailment. When he died on March 26, 1797, he was preparing an agricultural volume. He had amassed a respectable rock collection, which was donated by one of his sisters to the Royal Society of Edinburgh, then later passed to the university museum. The collection has since been lost. Though he devoted himself to geological studies, Hutton was widely read and well versed in a variety of subjects. He had published works on agriculture, meteorology, chemistry, the theory of matter, moral philosophy, and metaphysics.

James Hutton was a sociable man with a winning personality. Though he never married, he had many close friends and staunch supporters. He had one illegitimate son, James, born around 1747, with whom he remained in contact throughout his life. His activities were not limited to promoting his own interests; he volunteered his talents to a variety of causes. He was an active member on a committee involved in managing a project to join the Forth and Clyde Rivers with a canal. In 1788 he was elected a foreign member of the French Royal Society of Agriculture.

SUPPORT FOR HUTTON'S THEORY

After Hutton's death Scottish geologist and chemist James Hall published evidence supporting his friend's theory. Hall initially had rejected Hutton's theory, but over time and after numerous discussions and tours around Britain with Hutton, he became convinced of the truth of the geological cycle. Hall tried to persuade Hutton to perform certain experiments that would support his claims, but Hutton did not deem them necessary. Hutton felt the principles he delineated were clearly evident by observing nature and that nothing in a laboratory could significantly replicate the exquisite power of nature. Out of respect for Hutton, Hall refrained from pushing the issue. But after his death Hall published several experiments that challenged the objections to Hutton's ideas and brought his theory into public prominence.

Hall's first experiment demonstrated that igneous rocks could be converted to crystalline rocks. Neptunists did not believe that igneous rocks were once liquid but thought that if they were, they should turn into glass upon cooling, not crystalline rocks. By slowing down the cooling process, Hall was able to form an opaque crystalline material after melting fused basalt. Some were impressed by this. Others thought the results were sketchy, that perhaps some component was lost during the reaction that changed the actual chemical composition of the material. Next, Hall attacked the idea that marble could not be produced from limestone. It was thought that carbon dioxide would escape as a gas and only quicklime would result. So Hall heated limestone (a powdered chalk) in a gun barrel, sealed in order to allow immense pressure to build up. This prevented the escape of any volatile components during the heating. Then he slowly cooled it and found marble inside! In another experiment Hall produced consolidated sandstone from heating sand with salt water. Eventually, the series of more than 500 experiments Hall performed in his quest to validate Hutton's claims earned him the title of founder of experimental geology and geochemistry.

In 1802 one of Hutton's loyal contemporaries, John Playfair, wrote a biography of Hutton titled *Illustrations of the Huttonian Theory*. In it he not only discussed the life of the now famous geologist but explained Hutton's theory much more clearly than Hutton had managed to do himself. Thirty years later, when society was better prepared to accept the notion that the world was more than 6,000 years old and that it was continually evolving, Playfair's interpretation helped the scientific community adopt Hutton's vision.

Today Hutton's ideas are summarized in the principle of uniformitarianism, which holds that the physical and chemical processes that occur today are the same as those that formed geological structures in the past, though perhaps on an altered timescale. Uniformitarianism may be summarized as "the present is the key to the past," a tenet that forms the basis of modern geology.

See also GRANITE, GRANITE BATHOLITH; HISTORICAL GEOLOGY; UNCONFORMITIES; WERNER, A. G.

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Huygens, Christian (1629–1695) Dutch *Mathematician, Astronomer, Physicist* Christian Huygens was born on April 14, 1629, in The Hague, the Netherlands, son of Constantijn Huygens. He attended the University of Leiden and the College of Breda in the southern Netherlands, where he studied law and mathematics before becoming interested in science. Huygens is best known for his contributions showing that light consists of waves, which led to the current model explaining light using the concept of wave-particle duality. This is a quantum mechanical concept whereby all matter and energy exhibit both wave- and particle-like properties. Christian is also credited with developing many concepts of modern calculus.

Huygens was fascinated with mathematics, and in 1657 he wrote and published the first book on probability theory. For some years he experimented with clocks and pendulums, being one of the first to notice the resonance of pendulums, whereby two pendulums mounted on the same beam will adjust to swing in perfectly opposite directions. Huygens made many astronomical observations, including descriptions of Saturn's rings, and one of the first observations of Mercury making a transit over the Sun.

The Royal Society of London elected Huygens a member in 1663, then in 1666 he took a position with the French Academy of Sciences in Paris under the patronage of King Louis XIV. He worked from the Paris Observatory making many astronomical observations and published these in 1684 as his *Astroscopia Compendiaria*. Huygens was a firm believer in life on other planets, and in the liberal political atmosphere of the Netherlands in the 1600s he published his ideas on extraterrestrial life in his *Cosmotheoros* (The celestial worlds discovered: or, conjectures concerning the inhabitants, plants and productions of the worlds in the planets). This is in stark contrast to the political climate elsewhere in Europe at that time; by contrast, Giordano Bruno was burned at the stake in Italy for publicizing similar ideas in 1600.

In 1681 Huygens became seriously ill and returned to The Hague. He was not allowed to return to France later because of the political climate there. Christian Huygens died in The Hague on July 8, 1695.

See also ASTRONOMY; CONSTELLATION; COPERNICUS, NICOLAUS; EINSTEIN, ALBERT; LIFE'S ORIGINS AND EARLY EVOLUTION; MERCURY; PTOLEMY, CLAUDIUS PTOLEMAEUS; SATURN.

hydrocarbons and fossil fuels Hydrocarbons are gaseous, liquid, or solid organic compounds consisting of hydrogen and carbon. Petroleum is a mixture of different types of hydrocarbons (a type of fossil fuel) derived from the decomposed remains of plants and animals trapped in sediment, and can be used as fuel. When plants and animals are alive, they absorb energy from the Sun (directly through photosynthesis in plants, indirectly through consumption in animals) to make complex organic molecules that, after they die, decay to produce hydrocarbons and other fossil fuels. If organic matter is buried before it is completely decomposed, some "solar energy" may become stored in the rocks as fossil fuels (less than 1 percent of total organic matter gets buried). In most industrial nations the chief source of energy is fossil fuels.

The type of organic matter that gets buried in sediment plays an important role in the type of fossil fuel that forms. Shales and muds bury oceanic organisms (such as bacteria and phytoplankton), and the biomolecules (including proteins, carbohydrates, and lipids) produced by them form oil and natural gas when heated. The resins, waxes, lignins, and cellulose common to terrigenous plants (such as trees and bushes) form coals. Incompletely broken down organics in shale form kerogens, or oil shales, which require additional heat to convert to oil. Although this process could be done in the lab, it would take exceedingly long under normal laboratory conditions. In some tectonic settings in the Earth the conditions of temperature and pressure are just right to convert buried organic material to fossil fuels, forming the deposits in use today.

The first people on the planet to use oil were the ancient Iraqis, 6,000 years ago. Oil is fluid and is lighter than water, which strongly influences where it is found. An oil "pool" is an underground accumulation of oil and gas occurring in the pore spaces of rock. An oil field is a group of oil pools of similar type.

Once oil forms from the organic material, it migrates upward until it seeps out at the surface or encounters a trap. The migration of oil is like the movement of groundwater. Migration is slow, and since petroleum is lighter than water, water forces it upward to the tops of the traps. Because oil eventually finds its way to the surface, most oil is found in relatively young rocks.

The formation of oil requires that the source has been through a critical range of pressure and temperature conditions, known as the oil window. If the geothermal gradient is too low or too high, oil will not form. Oil and gas can accumulate only if five basic requirements are met. First, an appropriate source rock is needed to provide the oil. Second and third, a permeable reservoir with an impermeable roof rock is required. Fourth, a trap (stratigraphic or structural) is needed to hold the oil, and, finally, the formation of the trap must have occurred before the oil has escaped from the system. Thus it is statistically unlikely but fortunate if all five criteria are met and a petroleum deposit is formed.

Oil platform off California coast *(Susan Quinland-Stringer, Shutterstock, Inc.)*

Geologists know the location of approximately 1,000 gigabarrels (one gigabarrel is one thousand billion barrels), but much more remains to be discovered. Many of the unknown reserves include small deposits, but not tars, tar sands, and oil shales, which must be heated and extensively processed to make them useful, and thus are very expensive. The world now consumes 84 million barrels of oil per day; therefore known reserves will last an estimated 33 years. Oil is running out and is becoming an increasingly powerful political weapon. The oil-rich nations can effectively hold the rest of the world hostage, being that the world has become so dependent on oil. Future energy sources may include nuclear fuels, solar energy, hydroelectric power, geothermal energy, biomass, wind, gas hydrates, and tidal energy.

COAL

The most abundant fossil fuel, coal is a combustible rock that contains more than 50 percent (by weight) carbonaceous material formed by the compaction and induration of plant remains. Coal is a black sedimentary rock that consists chiefly of decomposed plant matter, with less than 40 percent inorganic material. Most coal formed in ancient swamps, where stagnant oxygen-deficient water prevented rapid decay and allowed burial and trapping of organic matter. In addition anaerobic bacteria in these environments attack the organic matter, releasing more oxygen and forming peat, a porous mass of organic matter that preserves recognizable twigs and other plant parts. Peat contains about 50 percent carbon and burns readily when dried. With increasing temperature and pressure, coal increases in rank, along with an increase of carbon content. In this process peat is transformed into lignite, bituminous coal, and eventually anthracite. Anthracite contains more than 90 percent carbon and is much shinier, brighter, and harder than bituminous coal and lignite. Coal is classified according to its rank and by the amount of impurities present.

NATURAL GAS

Natural gas forms naturally under normal conditions of temperature and pressure in the ground. Composed mostly of methane, natural gas also contains ethane, propane, butane, and pentane, with common impurities of inorganic gases including nitrogen, carbon dioxide, and hydrogen sulfide. Natural gas's origin is similar to that of other hydrocarbons, being derived from the decomposition of buried organic matter, but is simply the lighter end member of the spectrum of compositions of hydrocarbons. Being a gas, it contains only gaseous hydrocarbons having between one and five carbon atoms and no compounds with six or more carbon atoms. All types of organic matter can contribute to the formation of natural gas, when buried and heated to more than 320°F (160°C). Some natural gas is generated during the decomposition of coal and petroleum when they are heated above 320°F, whereas other gas is produced along with the generation of other hydrocarbons. An additional type of natural gas is biogenic methane, produced at shallow levels by the biodegradation of petroleum and when bacteria reduce carbon dioxide to methane in shallow sediments. Natural gas, abundant in shallow crustal reservoirs, is useful as a fossil fuel. Because it generally burns much cleaner than petroleum or coal, it is increasingly sought as an energy source. Reserves of natural gas are huge and may greatly exceed the remaining world reserves of petroleum.

GAS HYDRATES

Gas hydrates, or clathrates, are solid, icelike, water-gas mixtures that form at cold temperatures (40–43°F, or 4–6°C) and pressures above 50 atmospheres. They form on deep marine continental margins and in polar continental regions, often below the sea floor. The gas component is typically methane but may also contain ethane, propane, butane, carbon dioxide, or hydrogen sulfide, with the gas occurring inside rigid cages of water molecules. Anaerobic bacteria produce the methane by the biodegradation of organic material.

Estimates suggest that gas hydrates contain twice the amount of carbon present in all of the planet's known fossil fuel deposits, and as such they represent a huge, virtually untapped potential source of energy. However, the gases expand by more than 150 times the volume of the hydrates, they are located deep in the ocean, and methane is a significant greenhouse gas. These obstacles present significant technical problems to overcome before gas hydrates are widely mined as an energy source.

See also ARABIAN GEOLOGY; ASIAN GEOLOGY; BASIN, SEDIMENTARY BASIN; CARBON CYCLE; CARBONIFEROUS; ECONOMIC GEOLOGY; OCEAN BASIN; PASSIVE MARGIN; SEQUENCE STRATIGRAPHY.

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hydrosphere The hydrosphere is one of the Earth's external layers, consisting of the oceans, lakes, streams, glaciers, groundwater, and part of the atmosphere. The Earth is a water-rich planet, and the hydrosphere is a dynamic mass of liquid continuously on the move. The term *hydrologic cycle* describes changes, both long- and short-term, in the Earth's hydrosphere. Also known as the water cycle, the hydrologic cycle is powered by heat from the Sun, which causes evaporation, transpiration from plants, and accumulation of water into clouds. This water then moves in the atmosphere and precipitates as rain or snow, which then drains off in streams, evaporates, or moves as groundwater, eventually to begin the cycle over and over again. The time required for individual molecules of water to complete the cycle varies greatly; it may range from a few weeks for some molecules to many thousands of years for others.

Hydrology is the study of water in liquid, solid, and vapor form, on local to global scales. Studies performed by hydrologists include analysis of the properties of water, its circulation, and distribution on and below the surface in reservoirs, streams, lakes, oceans, and the groundwater system. Many hydrologists assess the movement of water through different parts of the hydrologic system and evaluate the influence of human activities on the system in attempts to maximize the benefits to society. Hydrology may also involve environmental and economic aspects of water use.

A view of the Earth from space reveals that water covers most of the surface, in stark contrast to every other planet. The water on the planet is responsible for many things that allow humans to habitate the Earth. Water lubricates the upper layers of the planet, allows plate tectonics to operate, controls climate and weathering, and is part of life itself, found in the bodies of complex fauna and flora to the interior of cells of the simplest single-celled organisms. The surface of the Earth is covered by about 70 percent water, and the human bodies are also composed of about 70 percent water.

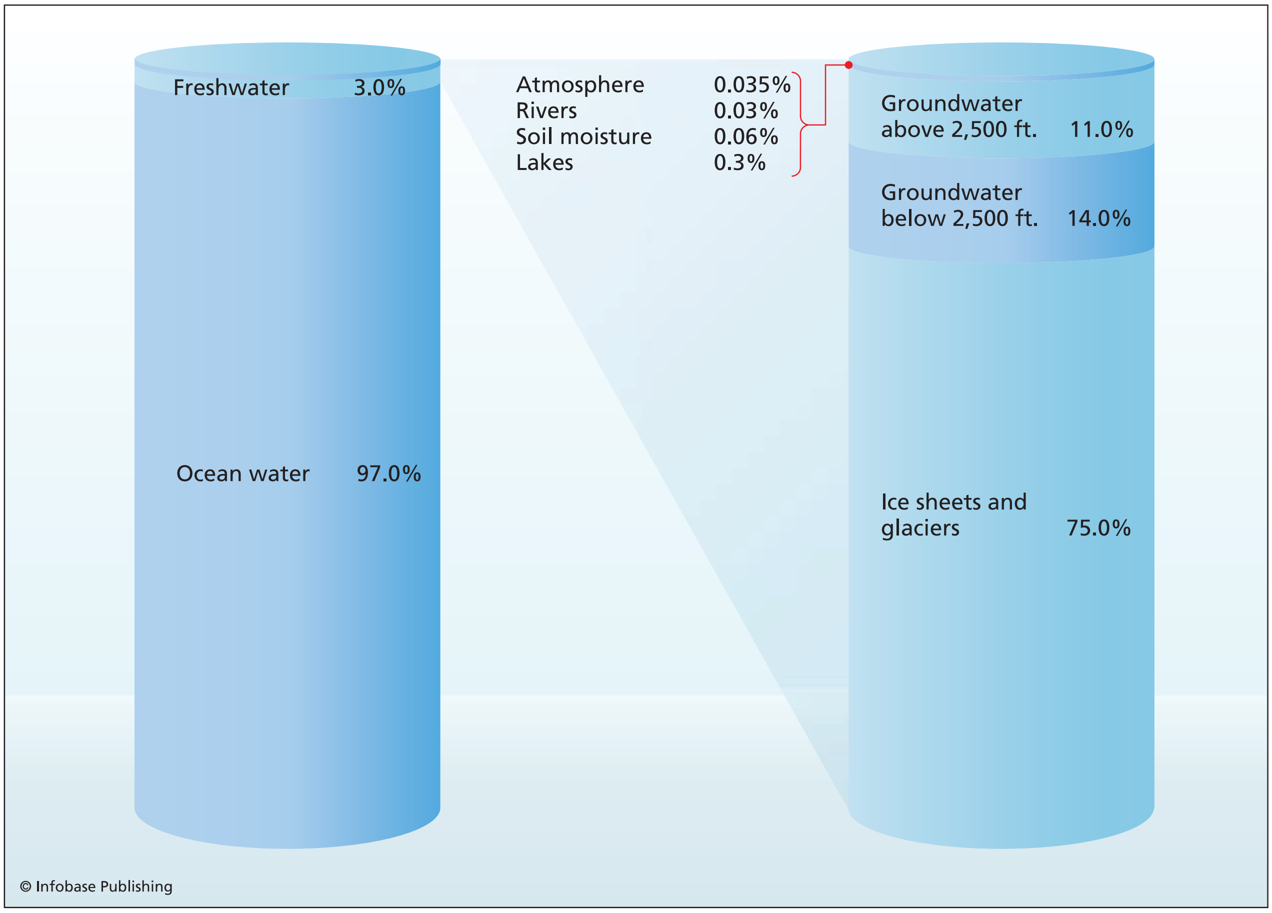
Water is the most precious resource on the planet, needed for sustaining all life, yet has also become the most threatened natural resource because of pollution and overuse. It can pose risks for catastrophic floods with increased urbanization of areas that used to store water on floodplains. Wars and political conflicts have always been fought over the ability to obtain freshwater, navigate rivers, irrigate farmland, and develop floodplains. Water rights pose difficult political issues in places where water is scarce, as in the American West and the Middle East. Since this is a finite world with a finite amount of freshwater, and the global population is growing rapidly, the management of freshwater will likely become an increasingly important issue for generations to come, yet public and political understanding of the science behind decisions on water use lags far behind political decision making and land use.

PROPERTIES OF WATER IN THE GROUND AND SURFACE WATER SYSTEMS

Even though most of the surface of the planet is covered with water, more than 97 percent of this water is salty and not readily usable for most human purposes. While the oceans may produce enormous amounts of food, offer transportation, and eventually provide a source of energy, humans require freshwater for drinking, agriculture, and industry. Freshwater is becoming the most valuable resource in the world, and because of its uneven distribution in a world with a rapidly growing population, there will be debate and outright conflict over the rights to and use of freshwater. At present, humans use more than half of all the freshwater that flows in rivers or that is stored in lakes, and this percentage is growing rapidly. Other sources of water are being exploited, including extraction from beneath the ground, to building reservoirs behind large dam projects.

The volume of groundwater is 35 times the volume of freshwater in lakes and streams, but overall freshwater accounts for less than 3 percent of the planet's water. The United States and other nations have come to realize that freshwater is a vital resource for their survival and are only recently beginning to appreciate that much of the world's water resources have become contaminated by natural and human-aided processes. Most drinking water in the United States comes from surface reservoirs or is purified from rivers, yet approximately 40 percent of drinking water in the country comes from groundwater reservoirs; about 80 billion gallons of groundwater are pumped out of these reservoirs every day in the United States. Groundwater is a limited resource since it is being pumped out of the ground faster than it is being replenished by natural processes.

Water is one of the most unusual substances in the entire solar system. Its unusual properties are responsible for controlling climate, life, and many



Bar graphs showing the distribution of water in hydrosphere. Ninety-seven percent of the planet's water in the hydrosphere is salt water located in the oceans. Three percent of the planet's water is fresh, but 75 percent of that small fraction is locked up in glacial ice. Most of the remaining freshwater is located underground in the groundwater system, and less than one-tenth of the world's freshwater is readily accessible to people in freshwater streams, rivers, and lakes.

processes on Earth. A water molecule (H_2O) consists of two hydrogen atoms bonded to one oxygen atom and is a polar molecule with a partial positive charge at the end with hydrogen, and a partial negative charge at the end containing the oxygen atom. This allows different water molecules to form weak bonds known as hydrogen bonds with other water molecules, as the positive end of one molecule bonds with the negative end of an adjacent molecule. The nature of this bond determines the properties of water, such as its melting/freezing point of 32°F (0°C) and boiling point of 212°F (100°C). Water may exist in three different states: as a solid (ice), liquid (water), or vapor (water vapor or steam). Since most of the planet has a temperature between 32° and 212°F (0°–100°C), most water exists in the liquid form.

One of the most unusual properties of water is that, like other compounds, it contracts and becomes denser as it cools, until about 39°F (4°C), at which point the cold water begins to become less dense again, becoming less dense than the warmer water. This property of water allows ice to float and causes water bodies to freeze from the top downward. If water was not so unusual, lakes and oceans would freeze from the bottom up and eventually become solid ice. No life would live beneath the seas, and the planet would become a giant cold iceball.

Water can also absorb a lot of heat or solar energy without becoming much warmer. This is because water has a high heat capacity; large water bodies do not change temperature rapidly and have a moderating climatic effect on nearby landmasses. It also takes a large amount of energy to change water from a liquid state to a vapor. To change liquid water to vapor, the water absorbs a lot of this heat energy from the source (say, the ocean) and carries this heat (the heat of vaporization) to the atmosphere, warming it. This is one of the most important heat-transfer processes on the surface of the planet, and it plays a large role in many atmospheric and climate effects. The processes can be appreciated on a personal level by feeling the cooling effect of allowing perspiration to evaporate from the body. Water may also sublimate, or move directly from the solid to the vapor state, or move from the groundwater system to water vapor in the atmosphere through the aid of transpiration in plants.

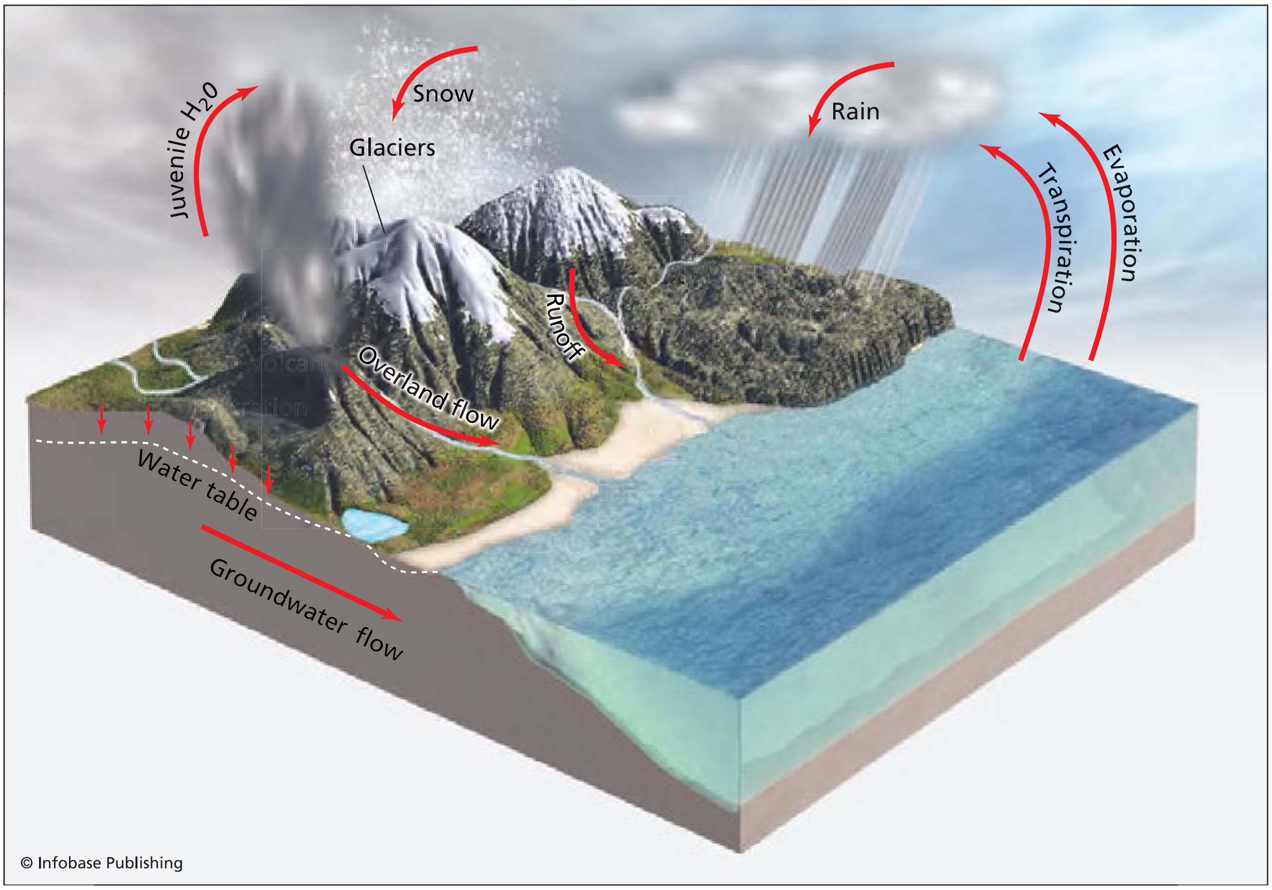
Water can also dissolve many substances with time, and can carry many substances in solution. Most water contains many mineral salts (such as sodium chloride, sea salt) derived from erosion of the landmasses and many dissolved gases from the atmosphere. The amount of gases dissolved in seawater is partly a function of temperature and plays a large role in climate and global warming.

THE HYDROLOGIC CYCLE

The water cycle describes the sum of processes operative in the hydrosphere, a dynamic mass of liquid continuously on the move between the different reservoirs on land and in the oceans and atmosphere. The hydrosphere includes all the water in oceans, lakes, streams, glaciers, atmosphere, and groundwater, although most water is in the oceans. The hydrologic, or water, cycle encompasses all of the changes, both long- and short-term, in the Earth's hydrosphere. It is powered by heat from the Sun, which causes water to change its state through evaporation and transpiration.

The water cycle can be thought of as beginning in the ocean, where energy from the Sun causes surface waters to evaporate, changing from the liquid to the gaseous states. Evaporation takes heat from the ocean and transfers it into the atmosphere. An estimated 102 cubic miles (425 cubic km^3) of water evaporate from the ocean each year, leaving the salts behind in the ocean. The water vapor then condenses into water droplets in clouds and eventually falls back to the Earth as precipitation. Ninety-two cubic miles (385 cubic km^3) falls directly back into the ocean, but about 26 cubic miles (111 km^3) of precipitation falls as rain or snow on the continents, transforming salty water of the oceans into freshwater on the land. Nearly three-fourths of this water (17 cubic miles, or 71 cubic km/yr) evaporates back to the atmosphere or is aided by the transpiration from plants, returning the water to the atmosphere. The other estimated 10 cubic miles (40 km^3) per year of water runs across the surface, some merging to form streams and rivers that eventually flow back into the ocean, and other parts of this 10 cubic miles per year seeping into the ground to recharge the groundwater system. Humans are now intercepting approximately half of the fresh surface water for drinking, agriculture, and other uses, making a significant impact on the hydrological cycle. Water that seeps into the groundwater system is said to infiltrate, whereas the water that flows across the surface is called runoff.

Understanding the water cycle reveals that freshwater is a renewable resource, replenished and cleaned every year, and available for reuse. It must be used wisely, however, since the quantities are limited, and small amounts of contamination can make entire parts of the system unusable. Freshwater is also supplied unevenly in space and time, with some areas receiving little, and other receiving freshwater in abundance. The water may come in floods or may be withheld, causing drought and suffering. Controlling the flow and usage of freshwater across large regions is one of the major challenges facing humans as the population of the planet grows exponentially and the water supply remains the same.



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The hydrologic cycle. Water evaporates from the oceans and forms clouds that cause precipitation to fall over the land and oceans. The rain and snow that falls on land can run off in rivers to the oceans, seep into the groundwater system, or be used by plants that then transpire the moisture back to the atmosphere. Water is continuously moving between the different parts of the hydrosphere.

RUNNING WATER AS AN EROSIVE AGENT

Water is an extremely effective erosional agent, including when it falls as rain and runs across the surface in finger-sized tracks called rivulets, and when it runs in organized streams and rivers. Water begins to erode as soon as the raindrops hit the surface—the raindrop impact moves particles of rock, breaking them free from the surface and setting them in motion.

During heavy rains the runoff is divided into overland flow and stream flow. Overland flow is the movement of runoff in broad sheets. Overland flow usually occurs over short distances before it concentrates into discrete channels as stream flow. Erosion performed by overland flow is known as sheet erosion. Stream flow is the flow of surface water in well-defined channels. Vegetative cover strongly influences the erosive power of overland flow by water. Plants that offer thicker ground cover and have extensive root systems prevent erosion much more than thin plants and crops that leave barren soil exposed between crop rows. Ground cover between that found in a true desert and savanna grasslands tends to be eroded the fastest, while tropical rain forests offer the best land cover to protect from erosion. First, the leaves and branches break the force of the falling raindrops, and the roots form an interlocking network that holds soil in place.

Under normal flow regimes streams attain a kind of equilibrium, eroding material from one bank and depositing it on another. Small floods may add material to overbank and floodplain areas, typically depositing layers of silt and mud over wide areas. During high-volume floods, however, streams may become highly erosive, removing entire floodplains that may have taken centuries to accumulate. The most severely erosive floods are found in confined channels with high flow, as where mountain canyons have formed downstream of many small tributaries that have experienced a large rainfall event, or in rivers that have been artificially channelized by levees. Other severely erosive floods have resulted from dam failures and, in the geological past, from the release of large volumes of water from ice-dammed lakes about 12,000 years ago. The erosive power of these floodwaters dramatically increases when they reach a velocity known as supercritical flow, at which time they can cut through alluvium with ease and even erode bedrock channels. Luckily supercritical flow cannot be sustained for long periods of time, as the effect of increasing the channel size causes the flow to self-regulate and become subcritical.

Cavitation in streams can also cause severe erosion. Cavitation occurs when the stream's velocity is so high that the vapor pressure of water is exceeded and bubbles begin to form on rigid surfaces. These bubbles alternately form then collapse with tremendous pressure, and are thus an extremely effective erosive agent. Cavitation is visible on some dam spillways, where bubbles form during floods and high discharge events, but it is different from the more common and significantly less erosive phenomenon of air entrapment by turbulence, which accounts for most air bubbles observed in white water streams.

WATER AS A RESOURCE

Since freshwater is essential for life, it may be considered an economic resource to manage effectively. Water is needed for drinking, irrigation, household, recreational, and industrial applications. In the United States agriculture uses about 43 percent of all water resources, and industry uses another 38 percent. On a global scale irrigation for agriculture accounts for an even higher percentage of water use, an estimated 69 percent of total water consumption, whereas industry uses only about 15 percent of water on a global scale. Most of the rest of the water is used by households, for drinking, washing, watering lawns, pools, and other benefits of affluent society. Americans use an average of 1,585 gallons (6,000 L) of water a day, compared with a bare one-half gallon (~2 L) a day needed for survival. Americans use about two to four times as much water as inhabitants of Western Europe, and much more than people in drought- and poverty-stricken countries in Africa and the rest of world.

Water resources include any source of water potentially available for human use, including lakes, rivers, rainfall, in reservoirs, and the groundwater system. About two-thirds of the freshwater available on the planet is currently stored in the frozen polar ice caps and in glaciers. Many nations and regions are using the remaining water in streams, lakes, rivers, reservoirs, and the groundwater system faster than the systems are being resupplied by rainfall. Such use is not sustainable, and in time the cost of water will skyrocket, to reflect this supply-and-demand problem. Taxes on water use in Western European countries are already much higher than in the United States. Taxes may be imposed to develop more economical sources of water, such as more energy-efficient desalination plants along coastal communities.

WATER AS A HAZARD

While the supply of clean freshwater is barely able to meet present demands and is expected to become a bigger problem, sometimes there is too much water in one place at one time, creating hazards of another kind. When rains, heavy snowmelts, or combinations of these events bring more water than normal into populated areas, floods result. Many floods cause significant damage and destruction because over the past couple of centuries many cultures have moved large segments of their populations onto floodplains. Floodplains are the flat areas adjacent to rivers that naturally flood. Ancient cultures used these floods and the rich organic mud that covered the floodplains during the floods as natural fertilizers for farmlands. Now that many population centers have been built on floodplains, people regard these natural flood cycles as disasters. In fact about nine out of every 10 disaster proclamations by the U.S. government are for flood disasters, typically to provide funds to those who have built on floodplains. Additionally, many types of natural vegetation have been removed from hillsides, particularly in urban areas. This reduces the amount of infiltration of water into the hillsides and increases the amount and rate of surface runoff thereby increasing the danger of floods.

There are many categories of flood. Flash floods are characterized by huge volumes of water rushing out of mountain canyons, carrying mud, boulders, and every other kind of debris into valleys and lowlands. Floods associated with coastal storms bring high tides into coastal lowlands and back up river systems across deltas and coastal plains. Many regions experience slowly rising, long-lasting regional floods associated with spring snowmelts and unusually heavy rains that can last for weeks or months. Some high-latitude climate zones also experience floods in association with the spring breakup of ice on rivers. As the ice melts blocks move downriver, occasionally jamming and forming ice dams, which can cause rapidly rising ice-cold floodwater to cover the floodplains.

THE WORLD'S DIMINISHING FRESHWATER SUPPLY

On a global scale only about half of the world's population has a connection to a piped-water supply in the home, whereas 30 percent rely on wells or local village pipes, and about 20 percent have no access at all to clean water. World population is expected to grow by another 50 percent (another 3–4

A levee on the Mississippi River being overtopped, with water flooding farmlands in Winfield, Missouri, during Midwest floods of summer 2008 *(T. Kusky)*

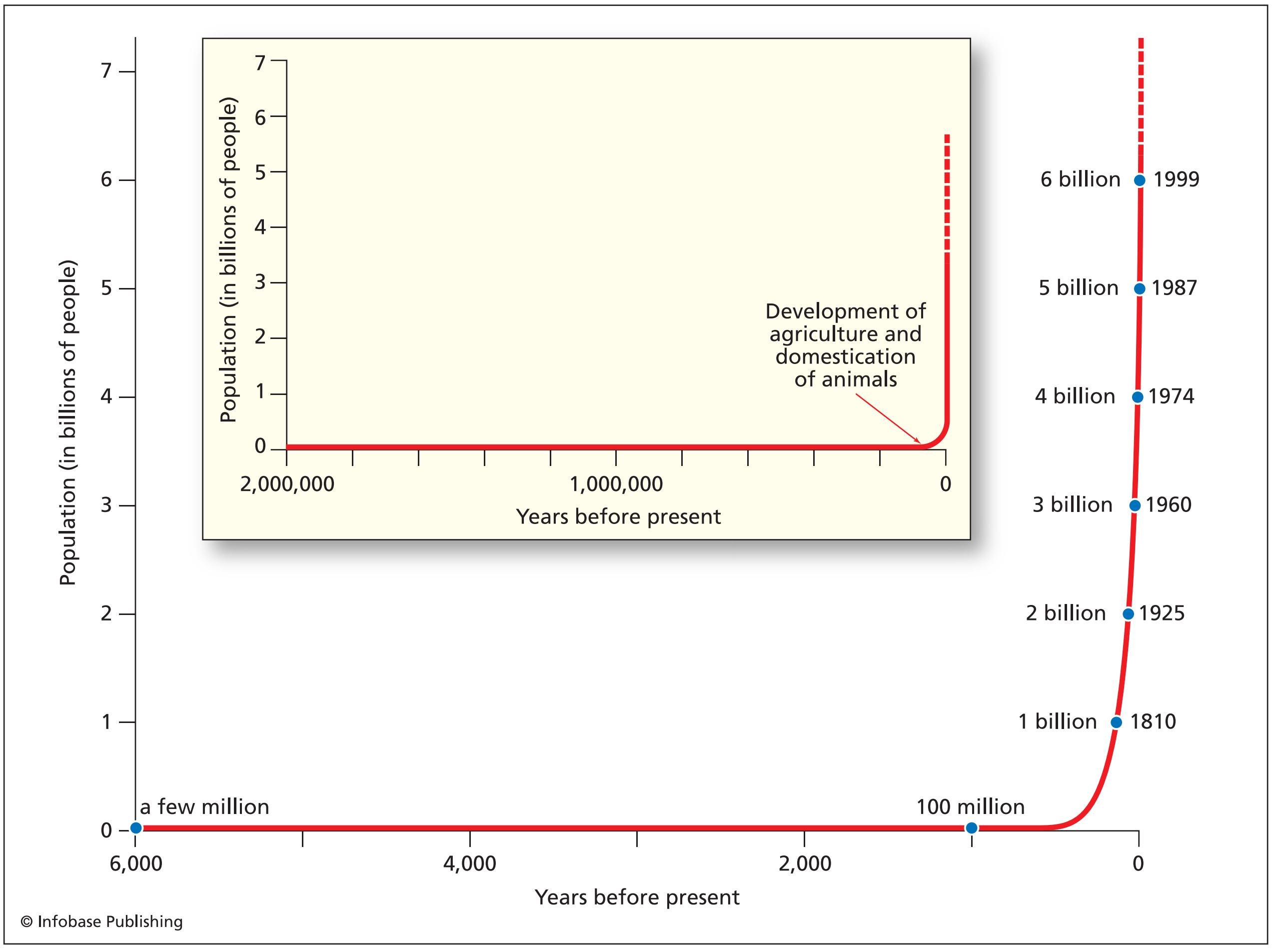
billion people) in the next 50 years, so huge investments are needed to maintain the existing water supply infrastructure and develop new supply networks. As population grows and water supplies remain the same or diminish, it is expected that in the next 10 years about half the world's population will not have access to clean drinking water. Most of those without access to clean water will live in Africa, South and Central America, and Southeast Asia. Many of the countries of the Middle East face a different problem—an extreme paucity of water of any kind. Many of these countries have other economic resources such as petroleum, and will have to invest in desalination to meet the needs of their populations.

Presently the highest water consumption per capita is in the United States, followed by the nations of Western Europe. As some developing nations, India and China in particular, grow in affluence, per capita water use is expected to rise dramatically. The huge populations of these countries will further stress the water resources and supply system on a global scale. As populations continue to move into urban areas, countries need to invest in huge water-supply and waste-water treatment facilities to ensure clean water for residents. In many places this has meant pumping water out of the ground, but the rate of extraction from groundwater aquifers is in many cases faster than the rate at which the water is being replenished, so this resource is being depleted.

Global climate change is starting to impact the hydrologic cycle in patterns of global rainfall and water supply. In some places rainfall is expected to diminish, while in other the amount of rainfall will increase. These changes in climate patterns may dictate massive changes in agricultural patterns and even in population trends within and among nations. It is time for scientists, politicians, and planners to discuss how to handle the coming changes on a dynamic planet.

MODIFICATIONS AND CHANNELIZATION OF RIVER SYSTEMS TO ALLEVIATE WATER SHORTAGES

Some desert and semiarid regions of the world have undergone rapid population explosions, necessitating the alteration of river courses to bring water to thirsty cities and to provide irrigation to farmlands to feed this growing population. In the American desert Southwest, California, and the Middle East, riverways have been extensively modified, regulated, and sometimes diverted hundreds of miles from their



Population curve showing the number of humans on Earth

natural course to provide water to places where people prefer to live.

Many examples of the effects of urbanization on flood intensity have been documented from California and the American desert Southwest. Urban areas like Los Angeles, San Diego, Tucson and Phoenix have documented the speed and severity of floods from similar rainfall amounts along the same drainage basin. These studies have documented that the floodwaters rise much more quickly after urbanization, and they rise up to four times the height of preurbanization, depending on the amount of paving over of the surface. The increased speed at which the floodwaters rise and the increased height to which they rise are directly correlated with the amount of land surface now covered over by roads, houses, and parking lots, blocking infiltration.

In natural systems floods gradually wane after the highest peak passes, and the slow fall of the floodwaters is related to the stream system being recharged by groundwater that seeped into the shallow surface area during the heavy rainfall event. In urbanized areas, however, the floodwaters not only rise quickly but also recede faster than in the natural environment. This is attributed to the lack of groundwater continuing to recharge the stream after the flood peak in urbanized areas.

Many other modifications in stream channels have been made in urbanized areas, with limited success in changing nature's course to suit human needs. Many stream channels have been straightened. This only causes the water to flow faster and have more erosive power. Straightening the stream course also shortens the stream length and thereby steepens the gradient. The stream may respond to this by aggrading and filling the channel with sediment in an attempt to regain the natural gradient.

American Desert Southwest

The history of development the American desert Southwest was crucially dependent on bringing water resources into this semiarid region. Much of California, especially the Los Angeles region, was regarded as worthless desert scrubland until huge water projects designed by the Bureau of Land Reclamation diverted rivers and resources from all over the West. In the years between 1911 and 1923 the California water department under the leadership of William Mulholland quietly purchased most of the water rights to the Owens Valley at the foot of the Sierra Nevada, then constructed a 233-mile (373-km) long aqueduct to bring this water to Los Angeles. When the local Owens Valley ranchers saw their water supplies dry up, they repeatedly dynamited the aqueduct, until Mulholland effectively declared war on the ranchers of the Owens Valley, protecting the aqueduct with a massive show of armed forces. This was the beginning of the present-day California aqueduct system, forming the branch known as the Los Angeles aqueduct.

The California aqueduct is presently 444 miles (715 km) long, and much of it consists of a concrete-lined channel typically 40 feet (12 m) wide and 30 feet (9 m) deep. The aqueduct has several sections, one starting at the San Joaquin–Sacramento River delta, to the San Luis Reservoir, then south to Los Angeles, with a branch heading to the coast in between. The California aqueduct meets the Los Angeles aqueduct north of Los Angeles, and the two systems distribute their water to the valley and thirsty residents of the city.

In the late 1800s geologist and explorer John Wesley Powell explored the West and warned that the water resources in the region were not sufficient for extensive settlement. But Congress went forward with a series of massive dam projects along the Colorado River, including the Hoover Dam, Glen Canyon Dam, and countless others across the region. These dams changed natural canyons and wild rivers into passive reservoirs that now feed large cities including Phoenix, Tucson, Las Vegas, Los Angeles, and San Diego. Use of water from the Colorado became so extensive that by 1969, where the river once flowed to the sea, no more water was flowing in the lower Colorado, the delta environment was destroyed, and water that Mexico used to rely on was no longer available.

Reliance on distant water sources to live in a desert may not seem the wisest of decisions, but much of California and the desert Southwest lives off of water diverted from resources in the Owens Valley, the Trinity River, the Colorado River, and many other western sources. Some conservationists, such as M. Reisner (author of *Cadillac Desert,* 1986) paint an ominous picture of development of the American desert Southwest that has many parallels to ill-fated societies elsewhere in world history. It is becoming increasingly difficult to continue to expand development in the desert and demand increasingly more water resources from a depleting source. Many of the soils are becoming too salty to sustain agriculture. With predictions of global climate change and expanding deserts, the future of the region must be critically examined so the nation can prepare for greater water crises.

Map of California showing the locations of the aqueducts bringing water from the mountains of the Sierra Nevada and from Mono Lake to water-thirsty Los Angeles

Water, Politics, and the Middle East

Water shortage, or drought, coupled with rapid population growth provides for extreme volatility in any region. In the Middle East water shortage issues are coupled with long-standing political and religious differences. The Middle East, stretching from North Africa and the Arabian Peninsula, through Israel and Lebanon to Turkey, and along the Tigris-Euphrates valleys, has only three major river systems and a few smaller rivers. The population stands at about 160 million. The Nile has an annual discharge of about 82 billion cubic yards (62.7 billion m^3), whereas the combined Tigris-Euphrates system has an annual discharge of 93 billion cubic yards (71 billion m^3). Some of the most intense water politics and drought issues in the Middle East arise from the four states that share the relatively small amounts of water of the Jordan River, with an annual discharge of fewer than 2 billion cubic yards (1.5 billion m^3). It has been estimated that with current water usage and population growth, many nations in this region have only 10–15 years before their agriculture and their security will be seriously threatened.

The region is arid, receiving 1–8 inches (2.5–20 cm) of rain per year, and has many drought years with virtually no rain. The Middle East has an annual population growth rate of about 3.5 percent, one of the highest in the world. Many countries in the region have inefficient agricultural practices that contribute to the growing problem of desertification in the region. Some of the problems include planting water-intensive crops, common flooding and furrow methods of irrigation, as well as spraying types of irrigation that lose much water to evaporation, and poor management of water and crop resources. These growing demands on the limited water supply, coupled with political strife resulting from shared usage of waterways that flow through multiple countries, has primed the region for a major confrontation over water rights. Many of the region's leaders have warned that water may be the cause of the next major conflict in the region—in the words of the late King Hussein of Jordan, water issues "could drive nations of the region to war."

Water use by individuals is by necessity much less in the Middle East than in the United States and other Western countries. For instance, every American has about 11,000 cubic yards (8,410 m^3) of freshwater potential to use each year, while citizens of Iraq (pre war) have about 6,000 (4,590 m^3), Turkey 4,400 (3,364 m^3), and Syria about 3,000 (2,294 m^3). Along the Nile Egyptians have about 1,200 cubic yards (917 m^3) available for each citizen. In the Levant Israel's have a freshwater potential of 500 cubic yards (382 m^3) per person per year, and Jordanians have only 280 cubic yards (214 m^3) per year.

The Nile, the second-longest river on Earth, forms the main water supply for nine North African nations, and disputes have grown over how to share this water as demand increases. The Blue Nile flows out of the Ethiopian Highlands and meets the White Nile in the Sudan north of Khartoum, then flows through northern Sudan into Egypt. The Nile is dammed at Aswan, forming Lake Nasser, then flows north through the fertile valley of Egypt to the Mediterranean.

The Nile is the only major river in Egypt, and nearly all of Egypt's population lives in the Nile Valley. About 3 percent of the nation's arable land stretches along the Nile Valley, but 80 percent of Egypt's water use goes to agriculture in the valley. The government has attempted to improve agricultural and irrigation techniques, which in many places have not changed appreciably for 5,000 years. If the Egyptians embraced widespread use of drip irrigation and other modern agricultural practices, then the demand for water could easily be reduced by 50 percent or more.

Egypt has initiated a massive construction and national reconstruction project whose aim to establish a new second branch of the Nile River, extending from Lake Nasser in the south, across the scorching Western Desert, and emerging at the sea at Alexandria. This ambitious project starts in the Tushka Canal area, where water is drained from Lake Nasser and is steered into a topographic depression that winds northward through some of the hottest, driest desert landscape on Earth. The government has been moving thousands of farmers and industrialists from the familiar Nile Valley into this national frontier, hoping to alleviate overcrowding. Cairo's population of 15 million is increasing at a rate of nearly 1 million per year. If successful, this plan could reduce the water demands on the limited resources of the river.

There are many obstacles to this plan. Will people stay in a desert where temperatures regularly exceed 120°F (49°C)? Will the water make it to Alexandria, having to flow through unsaturated sands and through a region where the evaporation rate is 200 times greater than the precipitation rate? How will drifting sands and blowing dust affect plans for agriculture in the Western Desert? Much of the downriver part of the Nile suffers from lower water and silt levels than needed to sustain agriculture and even the current land surface. So much water is used, diverted or dammed upstream that parts of the Nile Delta have actually started to subside (sink) beneath sea level. These regions desperately need to receive the annual silt layer from the flooding Nile to rebuild the land surface and prevent it from disappearing beneath the sea.

There are also political problems with establishing the new river through the Western Desert. Ethiopia contributes about 85 percent of the water to the Nile, yet it is experiencing severe drought and famine in the eastern part of the country. There is no infrastructure to transfer the water from the Nile to the thirsty lands to the east. Sudan and Egypt have longstanding disputes over water allotments, and Sudan

Map of the Middle East showing the main river systems. The area faces a rapidly growing population and a severe lack of water.

is not happy that Egypt is establishing a new river that will further Egyptians' use of the water. Water is currently flowing out of Lake Nasser, filling up several small lake depressions to the west, and sinking into and evaporating between the sands.

The Jordan River basin is host to some of the most severe drought and water-shortage issues in the Middle East. Israel, Jordan, Syria, Lebanon, and the Palestinians share the Jordan River water, and the resource is much more limited than water along the Nile or in the Tigris-Euphrates system. The Jordan River is only 100 miles (160 km) long and is made of three main tributaries, each with different characteristics. The Hasbani River has a source in the mountains of Lebanon and flows south to Lake Tiberias, and the Banias flows from Syria into the lake. The smaller Dan River flows from Israel. The Jordan River then flows out of Lake Tiberias and is joined by water from the Yarmuk flowing out of Syria into the Dead Sea, where any unused water evaporates.

The Jordan River is the source for about 60 percent of the water used in Israel, and 75 percent of the water used in Jordan. The other water used by these countries is largely from groundwater aquifers. Israel has almost exclusive use of the coastal aquifer along the Mediterranean shore, whereas disputes arise over use of aquifers from the West Bank and Golan Heights. These mountainous areas receive more rain and snowfall than other parts of the region and have some of the richest groundwater deposits. Since the 1967 war Israel has tapped the groundwater beneath the West Bank and now gets approximately 30–50 percent of its water supply from groundwater reserves beneath the mountains of the West Bank. The Palestinians get about 80 percent of their water from this mountain aquifer. A similar situation exists for the Golan Heights, though with lower amounts of reserves. These areas therefore have attained a new significance in terms of regional negotiations for peace in the region.

The main problems of water use stem from the shortage of water compared with the population, effectively making drought conditions. The situation is not likely to improve, given the alarming 3.5 percent annual population growth rate. Conservation efforts have only marginally improved the water use problem, and it is unlikely that there will be widespread rapid adoption of many of the drip-irrigation techniques used in Israel throughout the region. This is partly because it takes a larger initial investment in drip irrigation than in conventional furrow and flooding types of irrigation systems. Many farmers cannot afford this investment, even if it would improve their long-term yields and decrease their water use. When the Gaza Strip was turned over to Palestinian control, the authorities ripped out the drip irrigation systems and greenhouses set up by the Israelis and sold the parts for scrap. Now more water is needed to yield the same amount of crops.

Sporadic droughts have worsened this situation in recent years; in 1999 Israel cut in half the amount of water it supplies to Jordan, and Jordan declared drought conditions and mandated water rationing. Jordan currently uses 73 percent of its water for irrigation. If this number could be reduced by adoption of more efficient drip-irrigation, the current situation would be largely in control.

One possible way to alleviate the drought and water shortage would be to explore for water in unconventional aquifer systems such as fractures or faults, which are plentiful in the region. Many faults are porous and permeable structures that are several tens of meters wide, and thousands of meters long and deep. They may be thought of as vertical aquifers, holding as much water as conventional aquifers. If these countries were to be successful in exploring for and exploiting water in these structures, the water shortage and regional tensions might be reduced. This technique has proven effective in many other places in the Middle East, Africa, and elsewhere, and would probably work here as well.

Another set of problems plague the Tigris-Euphrates drainage basin and the countries that share water along their course. There are many political differences among Turkey, Syria, and Iraq, and the Kurdish people have been fighting for an independent homeland in this region. One of the underlying causes of dispute is also the scarce water supply in a drought-plagued area. Turkey is completing a massive dam construction campaign, with the largest dam being the Attatürk on the Euphrates. Overall Turkey is spending an estimated $32 billion on 22 dams and 19 hydroelectric plants. The aim is to increase the irrigated land in Turkey by 40 percent and to supply 25 percent of the nation's electricity through hydroelectric plants. This system of dams also now allows Turkey to control the flow of the Tigris and the Euphrates Rivers. If it pleases, Turkey can virtually shut off the water supply to downstream neighbors. At present Turkey is supplying Syria and Iraq with what it considers to be a reasonable amount of water, but Syria and Iraq claim the amount is inadequate. Political strife and even military action has resulted. Turkey is currently building a pipeline to bring water to drought-stricken Cyprus. Turkey and Israel are forging new partnerships and have been exploring ways to export water from Turkey and import it to Israel, which could help the drought in the Levant.

CAN DESALINATION HELP SOLVE THE WATER CRISIS?

With the hydrologic cycle changing through climate change and increased water use, it is important to find new sources of water. Desalination includes a group of water-treatment processes that remove salt from water; it is becoming increasingly more important as freshwater supplies dwindle and population grows, yet desalination is exorbitantly expensive and cannot be afforded by many countries. A number of different processes can accomplish desalination of salty water, whether it comes from the oceans or the ground. These are divided broadly into thermal processes, membrane processes, and minor techniques such as freezing, membrane distillation, and solar humidification. All existing desalination technologies require energy input to work and end up separating a clear fraction or stream of water from a stream enriched in concentrated salt that must be disposed of, typically by returning it to the sea.

Thermal distillation processes produce about half of the desalted water in the world. In this process salt water is heated or boiled to produce vapor that is then condensed to collect freshwater. There are many varieties of this technique, including processes that reduce the pressure and boiling temperature of water to cause flash vaporization effectively, using less energy than simply boiling the water. The multistage flash-distillation process is the most widely used around the world. In this technique steam is condensed on banks of tubes that carry chemically treated seawater through a series of vessels known as brine heaters with progressively lower pressures, and this freshwater is gathered for use. Multieffect distillation has been used for industrial purposes for many years. Multieffect distillation uses a series of vessels with reduced ambient pressure for condensation and evaporation, and operates at lower temperatures than multistage flash distillation. Salt water is generally preheated then sprayed on hot evaporator tubes to promote rapid boiling and evaporation. The vapor and steam is then collected and condensed on cold surfaces, where the concentrated brines run off. Vapor compression condensation is often used in combination with other processes or by itself for small-scale operations. Water is boiled, and the steam is ejected and mechanically compressed to collect freshwater.

Membrane processes operate on the principle of membranes being able to separate salts selectively from water. Reverse osmosis, commonly used in the United States, is a pressure-driven process in which water is pressed through a membrane, leaving the salts behind. Electrodialysis uses electrical potential, driven by voltage, to move salts selectively through a membrane, leaving freshwater behind. Electrodialysis operates on the principle that most salts are ionic and carry an electrical charge, so they can be driven to migrate toward electrodes with the opposite charge. Membranes are built that allow passage of only certain types of ions, typically either positively (cation) or negatively (anion) charged. Direct-current sources with positive and negative charge are placed on either side of the vessel, with a series of alternate cation and anion selective membranes placed in the vessel. Salty water is pumped through the vessel, the salt ions migrate through the membranes to the pole with the opposite charge, and freshwater is gathered from the other end of the vessel. Reverse osmosis appeared technologically feasible only in the 1970s. The main energy required for this process is for applying the pressure to force the water through the membrane. The salty feed water is preprocessed to remove suspended solids and chemically treated to prevent microbial growth and precipitation. As the water is forced through the membrane, a portion of the salty feed water must be discharged from the process to prevent the precipitation of supersaturated salts. Presently membranes are made of hollow fibers or spiral wound. Improvements in energy recovery and membrane technology has decreased the cost of reverse osmosis, and this trend may continue, particularly with the use of new nanofiltration membranes that can soften water in the filtration process by selectively removing calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions.

Several other processes have been less successful in desalination. These include freezing, which naturally excludes salts from the ice crystals. Membrane distillation uses a combination of membrane and distillation processes, which can operate at low temperature differentials but require large fluxes of salt water. Solar humidification was used in World War II for desalination stills in life rafts, but these are not particularly efficient because they require large solar collection areas, have a high capital cost, and are vulnerable to weather-related damage.

See also ATMOSPHERE; CLOUDS; FLOOD; GLACIER, GLACIAL SYSTEMS; OCEAN BASIN; RIVER SYSTEM.

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I

ice ages Times when the global climate was colder and large masses of ice covered many continents are referred to as ice ages. At several times in Earth's history large portions of the Earth's surface have been covered with huge ice sheets. About 10,000 years ago all of Canada, much of the northern United States, and most of Europe were covered with ice sheets, as was about 30 percent of the world's remaining landmass. These ice sheets lowered sea level by about 320 feet (100 m), exposing the continental shelves and leaving present-day cities including New York, Washington, D.C., and Boston 100 miles (160 km) from the sea. In the last 2.5 billion years several periods of ice ages have been identified, separated by periods of mild climate similar to that of today. Ice ages seem to form through a combination of several different factors, including the following:

- the amount of incoming solar radiation, which changes in response to several astronomical effects
- the amount of heat retained by the atmosphere and ocean, or the balance between the incoming and outgoing heat
- the distribution of landmasses on the planet. Shifting continents influence the patterns of ocean circulation and heat distribution, and a large continent on one of the poles causes ice to build up on that continent, increasing the amount of heat reflected to space, lowering global temperatures in a positive feedback mechanism.

Glaciations have happened frequently in the past 55 million years and could occur again at almost any time. In the late 1700s and early 1800s Europe experienced a "little ice age" during which many glaciers advanced from the Alps and destroyed small villages in their path. Ice ages have occurred at several other times in the ancient geologic past, including in the Late Paleozoic (about 350–250 million years ago), Silurian (435 million years ago), and Late Proterozoic (about 800–600 million years ago). During parts of the Late Proterozoic glaciation, it is possible that the entire Earth surface temperature was below freezing and the planet was covered by ice.

In the Late Proterozoic the Earth experienced one of the most profound ice ages in the history of the planet. Isotopic records and geologic evidence suggests that the entire Earth's surface was frozen, though some scientists dispute the evidence and claim that there would be no way for the Earth to recover from such a frozen state. In any case it is clear that in the Late Proterozoic, during the formation of the supercontinent Gondwana, the Earth experienced one of the most intense glaciations ever, with the lowest average global temperatures in known Earth history.

One of the longest-lasting glacial periods was the Late Paleozoic ice age, which lasted about 100 million years, indicating a long-term underlying cause of global cooling. Of the variables that operate on these longtime scales, the distribution and orientation of continents seems to have caused the Late Paleozoic glaciation. The Late Paleozoic saw the amalgamation of the planet's landmasses into the supercontinent of Pangaea. The southern part of Pangaea, known as Gondwana, consisted of present-day Africa, South America, Antarctica, India, and Australia. During the drift of the continents in the Late Paleozoic, Gondwana slowly moved across the South Pole, and huge ice caps formed on these southern continents during their passage over the pole. The global climate was much colder overall, with the subtropical belts becoming very condensed and the polar and subpolar belts expanding to low latitudes.

During all major glaciations a continent was situated over one of the poles. Currently Antarctica is over the South Pole, and this continent has huge ice sheets. When continents rest over a polar region, they accumulate huge amounts of snow that gets converted into several-mile-thick ice sheets that reflect more solar radiation back to space and lower global seawater temperatures and sea levels.

Another arrangement that helps initiate glaciations is continents distributed in a roughly N-S orientation across equatorial regions. Equatorial waters receive more solar heating than polar waters. Continents block and modify the simple east to west circulation of the oceans induced by the spinning of the planet. When continents are present on or near the equator, they divert warm water currents to high latitudes, bringing warm water to higher latitudes. Since warm water evaporates much more effectively than cold water, having warm water move to high latitudes promotes evaporation, cloud formation, and precipitation. In cold, high-latitude regions the precipitation falls as snow, which persists and builds up glacial ice.

The Late Paleozoic glaciation ended when the supercontinent of Pangaea began breaking apart, suggesting a further link between tectonics and climate. The smaller landmasses might not have been able to divert the warm water to the poles anymore, or perhaps enhanced volcanism associated with the breakup caused additional greenhouse gases to build up in the atmosphere, raising global temperatures.

The planet began to enter a new glacial period about 55 million years ago, following a 10-million-year-long period of globally elevated temperatures and expansion of the warm subtropical belts into the subarctic. This Late Paleocene global hothouse saw the oceans and atmosphere holding more heat than at any other time in Earth history, but temperatures at the equator were not particularly elevated. Instead the heat was distributed more evenly around the planet, leading to fewer violent storms (with a small temperature gradient between low and high latitudes) and more moisture overall in the atmosphere. Several factors contributed to the abnormally warm temperatures on the planet during this time, including a distribution of continents that saw the equatorial region free of continents. This allowed the oceans to heat up more efficiently, raising global temperatures. The oceans warmed so much that the deep ocean circulation changed, and the normally cold deep currents became warm. These melted frozen gases (known as methane gas hydrates) that had accumulated on the seafloor, releasing huge amounts of methane into the atmosphere. Methane is a greenhouse gas, and its increased abundance trapped solar radiation in the atmosphere, contributing to global warming. In addition volcanic eruptions released vast outpourings of mafic lavas in the North Atlantic Ocean realm, and the accompanying liberation of large amounts of CO_2 would have increased the greenhouse gases in the atmosphere and further warmed the planet. Global warming during the Late Paleocene was so extreme that about 50 percent of all single-celled organisms living in the deep ocean became extinct.

After the Late Paleocene hothouse, the Earth began a long-term cooling that continues today despite the present warming of the past century. This current ice age was marked by the growth of Antarctic glaciers, starting about 36 million years ago, until about 14 million years ago, when the Antarctic ice sheet covered most of the continent with several miles of ice. At this time global temperatures had cooled so much that many of the mountains in the Northern Hemisphere were covered with mountain and piedmont glaciers, similar to those in southern Alaska today. The ice age continued to intensify until 3 million years ago, when extensive ice sheets covered the Northern Hemisphere. North America was covered with an ice sheet that extended from northern Canada to the Rocky Mountains, across the Dakotas, Wisconsin, Pennsylvania, and New York, and on the continental shelf. At the peak of the glaciation (18,000–20,000 years ago) about 27 percent of the lands' surface was covered with ice. Midlatitude storm systems were displaced to the south, and desert basins of the southwest United States, Africa, and the Mediterranean received abundant rainfall and hosted many lakes. Sea level was lowered by 425 feet (130 m) to make the ice that covered the continents, so most of the world's continental shelves were exposed and eroded.

The causes of the Late Cenozoic glaciation are not well known but seem related to Antarctica coming to rest over the South Pole and other plate tectonic motions that have continued to separate the once contiguous landmasses of Gondwana, changing global circulation patterns in the process. Two of the important events seem to be the closing of the Mediterranean Ocean around 23 million years ago and the formation of the Panama isthmus 3 million years ago. These tectonic movements restricted the east-to-west flow of equatorial waters, causing the warm water to move to higher latitudes where evaporation promotes snowfall. An additional effect related to uplift of some high mountain ranges, including the Tibetan Plateau, has changed the pattern of the air circulation associated with the Indian monsoon.

The closure of the Panama isthmus correlates closely with the advance of Northern Hemisphere ice sheets, suggesting a causal link. This thin strip of land has drastically altered the global ocean circulation such that Pacific and Atlantic Ocean waters no longer communicate effectively, and it diverts warm currents to near-polar latitudes in the North Atlantic, enhancing snowfall and Northern Hemisphere glaciation. Since 3 million years ago the ice sheets in the Northern Hemisphere have alternately advanced and retreated, apparently in response to variations in the Earth's orbit around the Sun and other astronomical effects. These variations change the amount of incoming solar radiation on timescales of thousands to hundreds of thousands of years (Milankovitch Cycles). Together with the other longer-term effects of shifting continents, changing global circulation patterns, and abundance of greenhouse gases in the atmosphere, most variations in global climate can be approximately explained. This knowledge may help predict where the climate is heading and may help model and mitigate the effects of human-induced changes in the atmospheric greenhouse gases. If Earth is heading into another warm phase and the existing ice on the planet melts, sea level will quickly rise by 210 feet (64 m), inundating many of the world's cities and farmlands. Alternately, if the Earth enters a new ice sheet stage, sea levels will be lowered, and the planet's climate zones will be displaced to more equatorial regions.

See also ATMOSPHERE; GLACIER, GLACIAL SYSTEMS; GREENHOUSE EFFECT.

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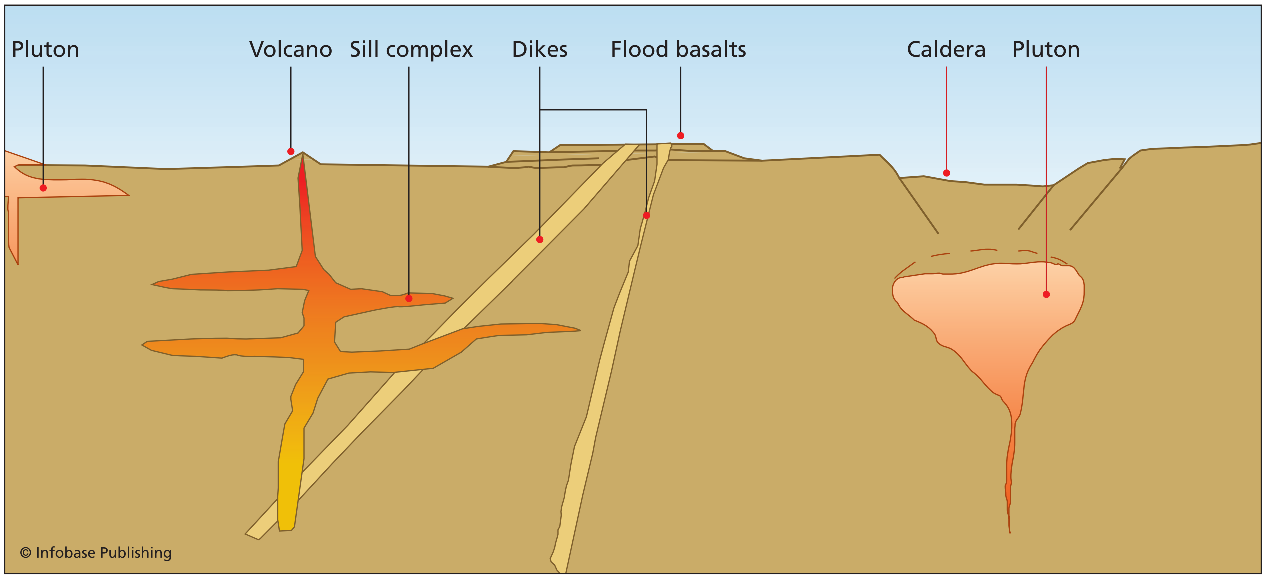
igneous rock A rock that has crystallized from a melt or partially molten material (known as magma) is classified as igneous. Magma is a molten rock within the Earth; if it makes its way to the surface, it is referred to as lava. Different types of magma form in different tectonic settings, and many processes act on the magma as it crystallizes to produce a wide variety of igneous rocks.

Most magma solidifies below the surface, forming igneous rocks (*igneous* is Latin for fire). Igneous rocks that form below the surface are called intrusive (or plutonic) rocks, whereas those that crystallize on the surface are called extrusive (or volcanic) rocks. Rocks that crystallize at a very shallow depth are known as hypabyssal rocks. Intrusive igneous rocks crystallize slowly, giving crystals an extended time to grow, thus forming rocks with large mineral grains that are clearly distinguishable to the naked eye. These rocks are called phanerites. In contrast, magma that cools rapidly forms fine-grained rocks. Aphanites are igneous rocks in which the component grains cannot be distinguished readily without a microscope and are formed when magma from a volcano falls or flows across the surface and cools quickly. Some igneous rocks, known as porphyries, have two populations of grain size—a large group of crystals (phenocrysts) mixed with a uniform groundmass (matrix) that fills the space between the large crystals. This indicates two stages of cooling, as when magma has resided for a long time beneath a volcano, growing big crystals. When the volcano erupts, it spews out a mixture of large crystals and liquid magma that then cools quickly.

Once magmas are formed from melting rocks in the Earth, they intrude the crust and can take several forms. A pluton is a general name for a large, cooled, igneous, intrusive body in the Earth. The specific type of pluton is based on its geometry, size, and relations to the older rocks surrounding it, known as country rock. Concordant plutons have boundaries parallel to layering in the country rock, whereas discordant plutons have boundaries that cut across layering in the country rock. Dikes are generally thin with parallel sides exhibiting tabular shapes and cut across preexisting layers, and are therefore said to be discordant intrusions. In contrast, sills are tabular intrusions oriented parallel to layers and said to be concordant intrusives. Volcanic necks are conduits connecting a volcano with its underlying magma chamber (a famous example of a volcanic neck is Devils Tower, Wyoming). Some plutons are so large that they have special names. Batholiths, for example, have a surface area of more than 60 square miles (100 km^2).

The mechanisms by which large bodies of magma intrude into the crust are debated by geologists and may be different for different plutons. One mechanism, assimilation, involves the hot magma melting the surrounding rocks as it rises, causing them to become part of the magma. As the magma cools, its composition changes to reflect the added melted country rock. Magmas can rise only a limited distance by assimilation because they quickly cool before they can melt their way significant distances through the crust. If the magma is under high pressure, it may forcefully push into the crust. One variation of this forceful emplacement style is diapirism, where the weight of surrounding rocks pushes down on the melt layer, which then squeezes up through cracks that can expand and extend, forming volcanic vents at the surface. Yet another mechanism is stopping. During pluton emplacement by stopping large



Forms of plutons and intrusive rocks, showing names given to various types of intrusions

blocks of the surrounding country rock get thermally shattered and drop off the top of the magma chamber and fall into the chamber, eventually melting and becoming part of the magma.

NAMES OF IGNEOUS ROCKS

The first stage of naming an igneous rock is determining whether it is phaneritic or aphanitic. The next step involves the determination of its mineral constituents. The chemical composition of magma is closely related to how explosive and hazardous a volcanic eruption will be. The variation in the amount of silica (SiO_2) in igneous rocks is used to describe the variation in composition of igneous rocks and the magmas that formed them, as shown in the table "Names of Igneous Rocks Based on Silica Content and Texture." Rocks with low amounts of silica (basalt, gabbro) are known as mafic rocks, whereas rocks with high concentrations of silica (rhyolite, granite) are silicic or felsic rocks.

THE ORIGIN OF MAGMA

Some of the variation in the different types of volcanic eruptions can be understood by examining what causes magmas to have such a wide range in composition. Magmas come from deep within the Earth, but what conditions lead to the generation of melts in the interior of the Earth? The geothermal gradient reflects the relationship between increased temperature and increased depth in the Earth, and it provides information about the depths at which melting occurs and the depths at which magmas form. The differences in the composition of the oceanic and continental crusts lead to differing abilities to conduct the heat from the interior of the Earth, and thus different geothermal gradients. The geothermal gradients show that temperatures within the Earth quickly exceed 1,832°F (1,000°C) with increasing depth, so why are these rocks not molten? The answer is that pressures are very high, and pressure influences the ability of a rock to melt. As the pressure rises, the temperature at which the rock melts also rises. The presence of water significantly modifies this effect of pressure on melting, because wet minerals melt at lower temperatures than dry minerals. As the pressure rises, the amount of water that can be dissolved in a melt increases. Increasing the pressure on a wet mineral has the opposite effect

NAMES OF IGNEOUS ROCKS BASED ON SILICA CONTENT AND TEXTURE

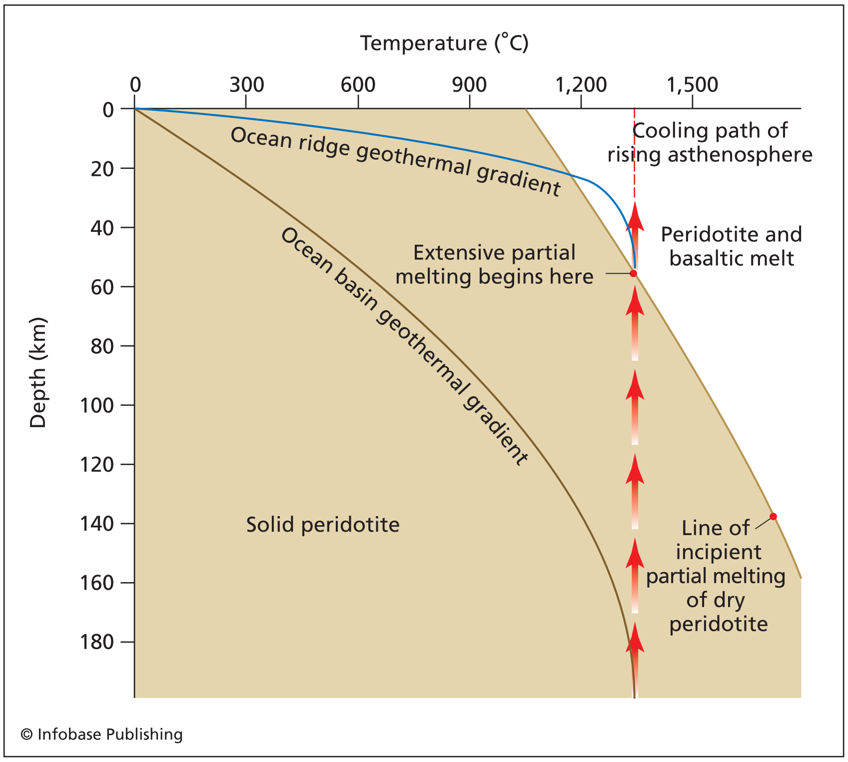
Magma Types	Percent SiO_2	Volcanic Rock	Plutonic Rock
Mafic	45–52%	Basalt	Gabbro
Intermediate	53–65%	Andesite	Diorite
Felsic	> 65%	Rhyolite	Granite

from increasing the pressure on a dry mineral—it decreases the melting temperature.

PARTIAL MELTING

If a rock melts completely, the magma has the same composition as the rock. Rocks are made of many different minerals, all of which melt at different temperatures. Therefore if a rock is slowly heated, the resulting melt, or magma, will first have the composition of the first mineral that melts and then the first plus the second mineral that melts, and so on. If the rock continues to melt completely, the magma will eventually end up with the same composition as the starting rock, but this does not always happen. Often the rock only partially melts so that the minerals with low melting temperatures contribute to the magma, whereas the minerals with high melting temperatures did not melt and are left as a residue (or restite). In this way the end magma can have a composition different from the rock it came from.

The phrase "magmatic differentiation by partial melting" refers to the forming of magmas with differing compositions through the incomplete melting of rocks. For magmas formed in this way, the composition of the magma depends on both the composition of the parent rock and the percentage of melt.



Typical geothermal gradient beneath the oceans, showing also the line of incipient partial melting of a dry peridotite

BASALTIC MAGMA

Partial melting in the mantle leads to the production of basaltic magma, which forms most of the oceanic crust. Examination of the mineralogy of the oceanic crust, which is dominated by olivine, pyroxene, and feldspar, reveals that little water is involved in the production of the oceanic crust. These minerals are all anhydrous, that is, without water in their structure. Dry partial melting of the upper mantle must lead to the formation of oceanic crust. By collecting samples of the mantle that have been erupted through volcanoes, we know that it has a composition of garnet peridotite (olivine + garnet + orthopyroxene). Analyzing samples of this in the laboratory, by raising its temperature and pressure so that it is equal to 62 miles (100 km) depth, shows that 10 percent to 15 percent partial melt of this garnet peridotite yields a basaltic magma.

Magma that forms at 50 miles (80 km) depth is less dense than the surrounding solid rock, so it rises, sometimes quite rapidly (at rates of half a mile, or one kilometer, per day measured by earthquakes under Hawaii). In fact it may rise so fast that it does not cool appreciably, erupting at the surface at more than 1,832°F (1,000°C), generating basaltic magma.

GRANITIC MAGMA

Granitic magmas are very different from basaltic magmas. They have about 20 percent more silica, and the minerals in granite (mica, amphibole) have a lot of water in their crystal structures. Granitic magmas are mostly exclusive to regions of continental crust. Inference from these observations leads to the conclusion that the source of granitic magmas is within the continental crust. Laboratory experiments suggest that when rocks with the composition of continental crust start to melt at temperature and pressure conditions found in the lower crust, a granitic liquid is formed, with 30 percent partial melting. These rocks can begin to melt by either the addition of a heat source, such as basalt intruding the lower continental crust, or by burying water-bearing minerals and rocks to these depths. The geological processes responsible for bringing the water-bearing minerals down to the level in the crust where the water can be released from their crystal structure, and lower the melting

Red granite at the coast *(TTphoto, Shutterstock, Inc.)*

temperature of surrounding rocks, are limited. Deep burial by sedimentation can cause the release of water, which escapes to the surface but does not usually cause the rocks to melt and form granite. In subduction zones water-bearing minerals can be carried to great depths in the Earth, and when they release water, the fluid can rise up into the overlying mantle and crust, and cause the granite melts to form in those regions.

These granitic magmas rise slowly (because of their high SiO_2 and high viscosities), until they reach the level in the crust where the temperature and pressure conditions are consistent with freezing or solidification of magma with this composition. This occurs about three to six miles (5–10 km) beneath the surface, which explains why large portions of the continental crust are not molten lava lakes. In many region, crust lies above large magma bodies (called batholiths) that are heated by the cooling magma. An example is Yellowstone National Park, where hot springs, geysers, and many other features indicate the presence of a large hot magma body at depth. Much of Yellowstone Park is a giant valley called a caldera, formed when an ancient volcanic eruption emptied an older batholith of its magma, and the overlying crust collapsed into the empty hole formed by the eruption.

ANDESITIC MAGMA

The average composition of the continental crust is andesitic, a composition that falls between that of basalt and rhyolite. Laboratory experiments show that partial melting of wet oceanic crust yields an andesitic magma. Remember that oceanic crust is dry, but after it forms it interacts with seawater, which fills cracks to several miles' (kilometers') depth. Also the sediments on top of the oceanic crust are full of water, but these are for the most part nonsubductable. Andesite forms above places where water is released from the subducted slabs, and it migrates into the mantle wedge above the subducting slab, forming water-rich magmas. These magmas then intrude the continental crust above, some forming volcanic andesites, others crystallizing as plutons of diorite at depth.

SOLIDIFICATION OF MAGMA

Just as rocks partially melt to form different liquid compositions, magmas can solidify to different minerals at different times to form different solids (rocks). This process also results in the continuous change in the composition of the magma—if one mineral is removed, the resulting composition is different. If some process removes these solidified crystals from the system of melts, a new magma composition results.

Several processes can remove crystals from the melt system, including squeezing melt away from the crystals or sinking of dense crystals to the bottom of a magma chamber. These processes lead to magmatic differentiation by fractional crystallization, as first described by Canadian petrologist Norman L. Bowen (1887–1956). Bowen systematically documented how crystallization of the first minerals changes the composition of the magma and results in the formation of progressively more silicic rocks with decreasing temperature.

See also ISLAND ARCS, HISTORICAL ERUPTIONS; MINERAL, MINERALOGY; OPHIOLITES; PLATE TECTONICS; VOLCANO.

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impact crater structures

Ample evidence shows that many small and some large meteorites have hit Earth frequently throughout time. Several hundred impact craters resulting from these events have been recognized to be preserved on continents, and a few have been recognized on the ocean floor. These craters exhibit a wide range of appearances. Some are small, only a few yards (m) across, such as the small, approximately 5,000-year-old craters at Henbury in the Northern Territories of Australia, while others are up to hundreds of miles (hundreds of km) across, such as the Precambrian Vredefort dome in South Africa. Eyewitness accounts describe many events, such as fireballs in the sky, recording the entry of a meteorite into the Earth's atmosphere, to the huge explosion over Tunguska, Siberia, in 1980 that leveled thousands of square miles (km) of trees and created atmospheric shock waves that traveled around the world. Many theories have been proposed for the Tunguska event, the most favored of which is the impact of a comet fragment with Earth. Fragments of meteorites are regularly recovered from places like the Antarctic ice sheets, where rocky objects on the surface have no place to come from but space. Although meteorites may appear as flaming objects moving across the night skies, they are generally cold, icy bodies when they land on Earth, as only their outermost layers get heated from the deep freeze of space during their short transit through the atmosphere.

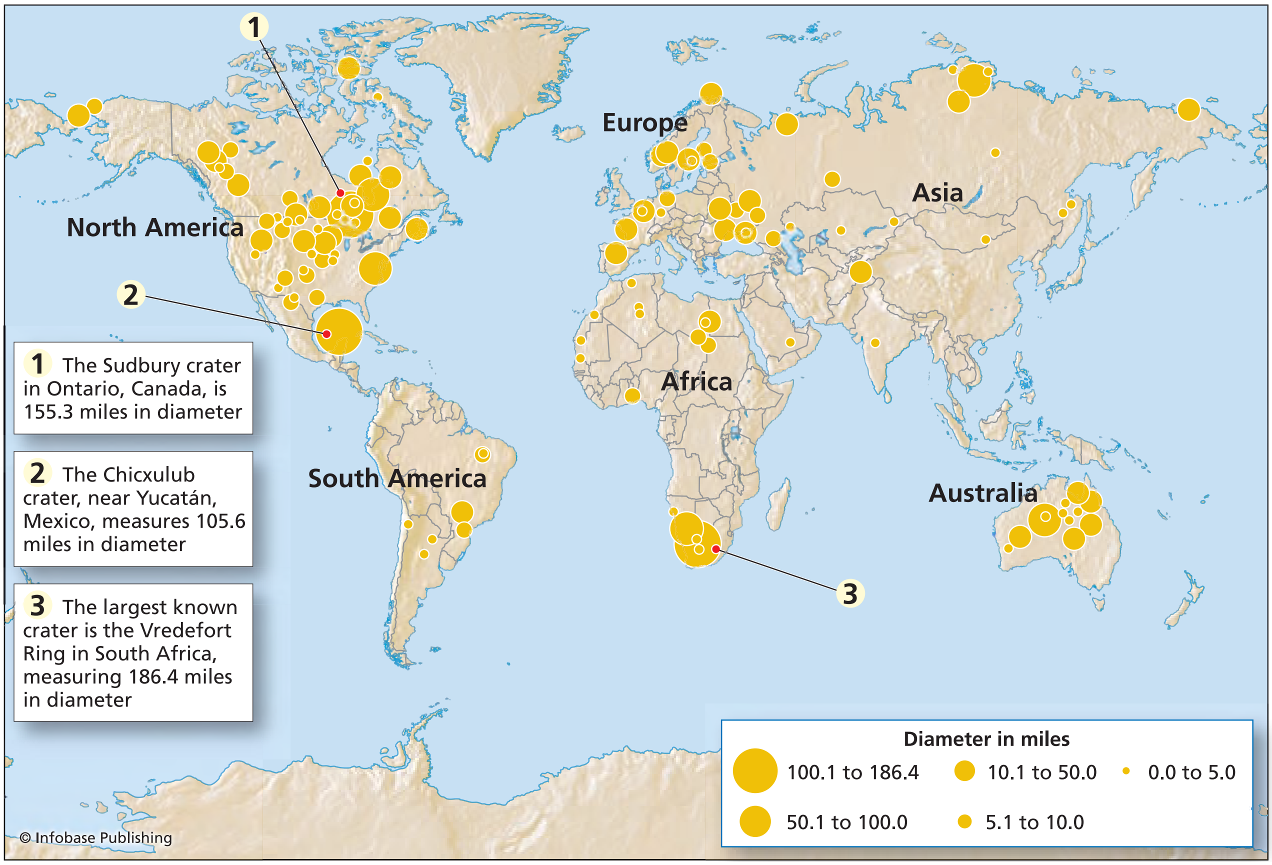
Most meteorites that hit Earth originate in the asteroid belt, situated between the orbits of Mars and Jupiter. There are at least a million asteroids in this belt with diameters greater than 0.6 miles (1 km), 1,000 with diameters greater than 19 miles (30 km), and 200 with diameters greater than 62 miles (100 km). These are thought to be either remnants of a small planet that was destroyed by a large impact event or perhaps fragments of rocky material that failed to coalesce into a planet, probably owing to the gravitational effects of the nearby massive planet Jupiter. Most scientists favor the second hypothesis but recognize that collisions between asteroids have fragmented a large body to expose a planetlike core and mantle now preserved in the asteroid belt.

Other objects from space may collide with Earth. Comets are masses of ice and carbonaceous material mixed with silicate minerals thought to originate in the outer parts of the solar system, in a region called the Oort Cloud. Other comets have a closer origin, in the Kuiper belt just beyond the orbit of Neptune. Small, icy Pluto, long considered the outermost planet, was recently reclassified from a planet to a dwarf planet, and may actually be a large Kuiper belt object. Comets may be less common near Earth than meteorites, but they still may hit Earth, with severe consequences. There are estimated to be more than a trillion comets in our solar system. Since they are lighter than asteroids and have water- and carbon-rich compositions, many scientists have speculated that cometary impact may have brought water, the atmosphere, and even life to Earth.

SURVEY OF IMPACT CRATERS ON EARTH AND THE MOON

Impact craters are known from every continent including Antarctica. Several hundred impact craters have been mapped and described in detail by geologists, and some patterns about the morphology, shape, and size of the craters have emerged from these studies. The most obvious variations in crater style and size are related to the size of the impacting meteorite, but other variations depend on the nature of the bedrock or cover, the angle and speed of the impact, and what the impactor was—rock or ice. Impacts are known from all ages and are preserved at various states of erosion and burial, allowing study of the many different levels of cratering and a better understanding of the types of structures and rocks produced during impacts.

The collision of meteorites with Earth produces impact craters, which are generally circular, bowl-shaped depressions. There are more than 200 known impact structures on Earth, although processes of weathering, erosion, volcanism, and tectonics have undoubtedly erased many thousands more. The Moon and other planets show much greater densities of impact craters, and since Earth has a greater gravi-



Map of impact craters on Earth—larger circles representing larger impact craters

tational pull than the Moon, it should have been hit by many more impacts than the Moon.

Meteorite impact craters have a variety of forms but are of two basic types. Simple craters are circular, bowl-shaped craters with overturned rocks around their edges, and are generally fewer than three miles (5 km) in diameter. They are thought to have been produced by impact with objects of fewer than 100 feet (30 m) in diameter. Examples of simple craters include the Barringer Meteor Crater in Arizona and Roter Kamm in Namibia. Complex craters are larger, generally greater than two miles (3 km) in diameter. They have an uplifted peak in the center of the crater and a series of concentric rings around the excavated core of the crater. Examples of complex craters include Manicougan, Clearwater Lakes, and Sudbury in Canada; Chicxulub in Mexico; and Gosses Bluff in Australia.

The style of impact crater depends on the size of the impacting meteor, the speed at which it strikes the surface, and, to a lesser extent, the underlying geology and angle at which the meteor strikes Earth. Most meteorites hit Earth with a velocity between 2.5 and 25 miles per second (4–40 km/sec), releasing tremendous energy when they hit. Meteor Crater in Arizona was produced about 50,000 years ago by a meteorite approximately 100 feet (30 m) in diameter that hit the Arizona desert, releasing the equivalent of 4 megatons (3.6 megatonnes) of TNT. The meteorite body and a large section of the ground at the site were suddenly melted by shock waves from the impact, which released about twice as much energy as the eruption of Mount Saint Helens. Most impacts generate so much heat and shock pressure that the entire meteorite and a large amount of the rock it hits are melted and vaporized. Temperatures may exceed thousands of degrees within a fraction of a second as pressures increase a million times atmospheric pressure during passage of the shock wave. These conditions cause the rock at the site of the impact to accelerate downward and outward, and then the ground rebounds and tons of material are shot outward and upward into the atmosphere.

Impact cratering is a complex process. When the meteorite strikes, it explodes, vaporizes, and sends shock waves through the underlying rock, compressing the rock and crushing it into breccia, and ejecting material (conveniently known as ejecta) up into the atmosphere, from where it falls out as an ejecta blanket around the impact crater. Large impact events may melt the underlying rock forming an impact melt and may crystallize distinctive minerals that form only at exceedingly high pressures.

After the initial stages of the impact crater-forming process, the rocks surrounding the excavated crater slide and fall into the deep hole, enlarging the diameter of the crater, typically making it much wider than it is deep. Many of the rocks that slide into the crater are brecciated or otherwise affected by the passage of the shock wave, and may preserve these effects as brecciated rocks, high-pressure mineral phases, shatter cones, or other deformation features.

Impact cratering was probably a much more important process in the early history of Earth than it is at present. The flux of meteorites from most parts of the solar system was much greater in early times, and it is likely that impacts totally disrupted the surface in the early Precambrian. At present the meteorite flux is about a hundred tons (91 tonnes) per day (somewhere between 10^7–10^9 kg/yr), but most of this material burns up as it enters the atmosphere. Meteorites that are about one-tenth of an inch to several feet (mm–m) in diameter produce a flash of light (a shooting star) as they burn up in the atmosphere, and the remains fall to Earth as a tiny glassy sphere of rock. Smaller particles, known as cosmic dust, escape the effects of friction and slowly fall to Earth as a slow rain of extraterrestrial dust.

Meteorites must be greater than 3 feet (1 m) in diameter to make it through the atmosphere without burning up from friction. The Earth's surface is currently hit by about one small meteorite per year. Larger-impact events occur much less frequently, with meteorites 300 feet (90 m) in diameter hitting once every 10,000 years, 3,000 feet (900 m) in diameter hitting Earth once every million years, and six miles (10 km) in diameter hitting every 100 million years. Meteorites of only several hundred feet (hundreds of m) in diameter could create craters about one mile (1–2 km) in diameter, or if they hit in the ocean, they would generate tsunamis, more than 15 feet (5 m) tall over wide regions. The statistics of meteorite impact show that the larger events are the least frequent.

Barringer Meteor Impact Crater, Arizona

One of the most famous and visited impact craters in the United States is the Barringer meteor impact crater in Arizona, the first structure almost universally accepted by the scientific community as a meteorite impact structure. The crater is 0.75 miles (1.2 km) across, and has an age of 49,000 years before present. Its acceptance as an impact crater did not come easily. The leading proponent of the meteorite impact model was Daniel Barringer, a mining company executive who argued for years against the

Barringer meteor impact crater, Arizona *(François Gohier/Photo Researchers, Inc.)*

powerful head of the U.S. Geological Survey, Grove K. Gilbert, who maintained that the crater was a volcanic feature. For years Daniel Barringer lost the argument because in his model the crater should have been underlain by a massive iron-nickel deposit from the meteorite, which was never found since the meteorite was vaporized by the heat and energy of the impact. By 1930, however, enough other evidence for the origin of the crater had been accumulated to convince the scientific community of its origin by impact from space.

Barringer crater is a small crater with a roughly polygonal outline partly controlled by weak zones (fractures and joints) in the underlying rock. The bedrock of the area is simple, consisting of a cover of alluvium, underlain by the thin Triassic Moenkopi sandstone, about 300 feet (90 m) of the Permian Kaibab limestone, and 900 feet (270 m) of the Permian Coconino sandstone. The rim of the crater is 148 feet (45 m) higher than the surrounding desert surface, and the floor of the crater lies 328 feet (100 m) lower than the surrounding average desert elevation. The rim of the crater is composed of beds of material that originally filled the crater but was thrown or ejected during the impact. The beds in the rim rocks are fragmented and brecciated, and the whole sequence that was in the crater is now upside down lying on the rim. The underlying beds are turned upward as the crater is approached, reflecting this powerful bending and overturning that occurred when the interior rocks were thrown onto the rim during the impact.

Although the large mass of iron and nickel that Daniel Barringer sought at the base of the crater does not exist, thousands of small meterorite fragments have been collected from around the outer rim of the crater, from as far away as four miles (7 km) from the crater. The soil around the crater, for a distance of up to six miles (10 km) is pervaded by meteorite dust, suggesting that the impacting meteorite vaporized on impact, and the debris settled around the crater in a giant dust cloud. Estimates of the size of the meteorite that hit based on the amount of meteorite debris found are about 12,000 tons (10,884 tonnes).

Several lines of evidence indicate an impact origin for Meteor crater. The widespread brecciation, or fragmentation, of the rim and presence of iron-rich shale from weathering of the meteorite is consistent with an impact origin. More important, high-temperature glasses and minerals are preserved that form almost exclusively during the high pressures of meteorite impact. In some places the rock has been melted into impact glasses that require temperatures and shock pressures obtained only during impact of an object such as a meteor. Some rare minerals that form only at high pressures have been found at Barringer crater, including high-pressure phases of quartz known as coesite and stishovite, and also small diamonds formed by high pressures associated with the impact.

Chicxulub Impact and the Cretaceous/Tertiary Mass Extinction

The geologic record of life on Earth shows that there have been several sudden events that led to the extinction of large numbers of land and marine species within a short interval of time, and many of these are thought to have been caused by the impact of meteorites with Earth. Many of the boundaries between geologic time periods have been selected based on these mass extinction events. Some of the major mass extinctions include that between the Cretaceous and Tertiary Periods, marking the boundary between the Mesozoic and Cenozoic Eras. At this boundary occurring 66 million years ago dinosaurs, ammonites, many marine reptile species, and a large number of marine invertebrates suddenly died off, and the planet lost about 26 percent of all biological families and numerous species. At the boundary between the Permian and Triassic Periods (which is also the boundary between the Paleozoic and Mesozoic eras), 245 million years ago, 96 percent of all species became extinct. Many of the hallmark lifeforms of the Paleozoic era were lost, such as the rugose corals, trilobites, many types of brachiopods, and marine organisms including many foraminifer species. Several other examples of mass extinctions have been documented from the geological record, including one at the boundary between the Cambrian and Ordovician Periods at 505 million years ago, when more than half of all families disappeared forever.

These mass extinctions have several common features that point to a common origin. Impacts have been implicated as the cause of many of the mass extinction events in Earth history. The mass extinctions seem to have occurred on a geologically instantaneous timescale, with many species present in the rock record below a thin clay-rich layer, and dramatically fewer species present immediately above the layer. In the case of the Cretaceous-Tertiary extinction, some organisms were dying off slowly before the dramatic die-off, but a clear, sharp event occurred at the end of this time of environmental stress and gradual extinction. Iridium anomalies have been found along most of the clay layers, considered by many to be the “smoking gun” indicating an impact origin as the cause of the extinctions. One-half million tons (454,000 tonnes) of iridium are estimated to be in the Cretaceous-Tertiary boundary clay, equivalent to the amount that would be contained in a meteorite with a six-mile (10-km) diameter. Other scientists argue that volcanic processes within Earth can produce iridium and that impacts are not necessary. Still other theories about the mass extinctions and loss of the dinosaurs exist, including that they died off from disease, insect bites, and genetic evolution that led to a great dominance of male over female species. Other rare elements and geochemical anomalies are present along the Cretaceous-Tertiary boundary, however, supporting the idea that a huge meteorite hit Earth at this time and was related in some way to the extinction of the dinosaurs, no matter what else may have been contributing to their decline at the time of the impact.

Other features have been found in the Chicxulub impact structure that support the impact origin for the mass extinctions. One of the most important is the presence of high-pressure minerals formed at pressures not reachable in the outer layers of Earth. The presence of the high-pressure mineral equivalents of quartz, including coesite, stishovite, and an extremely high-pressure phase known as diaplectic glass, strongly implicates an impacting meteorite, which can produce tremendous pressures during the passage of shock waves related to the force of the impact. Many of the clay layers associated with the iridium anomalies also have layers of tiny glass spherules thought to be remnants of melted rock produced during the impact that were thrown skyward, where they crystallized as tiny droplets that rained back on the planet's surface. They also have abundant microdiamonds similar to those produced during meteorite impact events. Layers of carbon-rich soot are also associated with some of the impact layers, and these are thought to represent remains of the global wildfires ignited by the impacts. Finally, some of the impact layers also record huge tsunamis that swept across coastal regions.

Many of these features are found around and associated with an impact crater recently discovered on Mexico's Yucatán Peninsula. The Chicxulub crater is about 66 million years old; half of it lies buried beneath the waters of the Gulf of Mexico, and half is on land. Tsunami deposits of the same age are found in inland Texas, much of the Gulf of Mexico, and the Caribbean, recording a huge tsunami, perhaps several hundred feet high (hundred m), generated by the impact. The crater is at the center of a huge field of scattered spherules that extends across Central America and through the southern United States. Chicxulub is a large structure, and is the right age to be the crater that records the impact at the Cretaceous-Tertiary boundary, thus fixing the extinction of the dinosaurs and other families.

The discovery and documentation of the meteorite crater on the Yucatán Peninsula, near the town of Chicxulub (meaning "tail of the devil") was a long process, but the crater is now widely regarded as the one that marks the site of the impact that caused the Cretaceous-Tertiary (K-T) mass extinction, including the loss of the dinosaurs. The crater was first discovered and thought to be an impact crater in the 1970s by Glen Penfield, a geologist working on oil exploration. He did not publish his results but presented ideas for the impact origin of the structure in scientific meetings in the 1980s. In 1981 University of Arizona geology graduate student Alan Hildebrand wrote about impact-related deposits around the Caribbean that had an age coincident with the Cretaceous-Tertiary boundary. These deposits include brown clay with an anomalous concentration of the metal iridium, thought to be from a meteorite, and some impact melts in the form of small beads called tektites. Hildebrand also wrote about evidence for a giant tsunami around the Caribbean at the K-T boundary but did not know the location of the crater. It was not until 1990 that Carlos Byars, a reporter for the *Houston Chronicle,* put the observations together and contacted Hildebrand, leading Hildebrand and Penfield to work together on realizing that they had located the crater and the deposits of the giant impact from the Cretaceous-Tertiary mass extinction.

Initially the Chixculub crater was thought to be about 110 miles (177 km) wide, but later studies have shown that it is a complex crater, and an additional ring was located outside the initial discovery. The crater is now regarded as being 190 miles (300 km) in diameter. The outermost known ring of the Chicxulub crater is marked by a line of sinkholes, where water moved along fractures and dissolved the underlying limestone.

The Chicxulub crater is buried under younger limestone, lying beneath 3,200 feet (1 km) of limestone that overlies 1,600 feet (500 m) of andesitic glass and breccia found only within the circular impact structure. These igneous rocks are thought to be impact melts, generated by the melting of the surrounding rocks during the impact event, and the melts rose to fill the crater immediately after the impact. Supporting this interpretation is the presence of unusual minerals and quartz grains that show evidence of being shocked at high pressures, forming distinctive bands through the mineral grains. The center depression of the crater is about 2,000 to 3,600 feet (609.6 to 1,097.3 m) deep compared with the same layers outside the crater rim, although the surface expression is now minimal since the crater is buried so deeply by younger rocks. The band of sinkholes that marks the outer rim of the crater suggests that the interior of the crater may have been filled with water after the impact, forming a circular lake.

The size of the meteorite that hit Chixculub is estimated to have been six miles (10 km) in diameter, releasing an amount of energy equal to 10^{14} tons of TNT. Recent studies suggest that the type of meteorite that hit Chicxulub was a carbonaceous chondrite, based on the chemistry and large amount of carbonaceous material found in pieces of the meteorite recovered from the impact.

The impact at Chicxulub was devastating for both the local and the global environment. The impact hit near the break between the continental shelf and the continental slope, so it ejected huge amounts of dust into the atmosphere from the shelf, and caused a huge mass of the continental shelf to collapse into the Gulf of Mexico and Caribbean. This in turn generated one of the largest tsunamis known in the history of the planet. This tsunami was thousands of feet (hundreds of m) tall on the Yucatán Peninsula and was still 165–330 feet (50–100 m) tall as it swept into the present-day Texas coastline, reaching far inland.

As the impact excavated the crater at Chicxulub, probably in less than a second, the meteorite was vaporized and ejected huge amounts of dust, steam, and ash into the atmosphere. As this material reentered the atmosphere around the planet it would have been heated to incandescent temperatures, igniting global wildfires and quickly heating surfaces and waters. At the same time tremendous earthquake waves were generated, estimated to have reached magnitudes of 12 or 13 on the open-ended Richter scale. This is larger than any known earthquake since then, and would have caused seismic waves that uplifted and dropped the ground surface by hundreds to a thousand feet (up to 300 m) at a distance of 600 miles (965 km) from the crater.

The impact generated huge amounts of dust and particles that would have been caught in the atmosphere for months after the impact, along with the ash from the global fires. This would block the sunlight and create in ice condition across the planet. Countering this effect is the release of huge amounts of carbon dioxide by the vaporization of carbonate rocks during the impact, which would have helped induce a greenhouse warming of climate that could have lasted decades. Together these effects wreaked havoc on the terrestrial fauna and flora that survived the fires and impact-related effects.

The Chicxulub crater and impact are widely held to have caused the mass extinction and death of the dinosaurs at the Cretaceous-Tertiary boundary. The global environment was considerably stressed before the impact, however, with marine planktonic organisms experiencing a dramatic decline before the impact (and a more dramatic one after the impact), and global temperatures falling before the crash. Some scientists argue that not all fauna, such as frogs, went extinct during the impact, and they should have if the impact was the sole cause of mass extinction. Others have argued that the age of the impact is not exactly the same age as the extinction, and may actually predate the extinction by up to 300,000 years. Some models suggest that the global environment was already stressed, and the impact was the final blow to the environment that caused the global mass extinction.

Manicouigan Crater, Ontario, Canada

At 62 miles (100 km) across, the Manicouigan structure in Ontario is one of the largest known impact structures in Canada, and the fifth-largest known impact structure on Earth. This circular, partly exposed crater was formed by the impact of a meteorite with a three-mile (5-km) diameter with Earth 214 million years ago, hitting what is now the Precambrian shield. The Manicouigan River flows south out of the south side of the crater and drains into the St. Lawrence River. For some time it was thought that the Manicouigan crater resulted from the impact that caused a mass extinction that killed 60 percent of all species on Earth at the Permian-Triassic boundary, but dating the impact melt showed that the crater was 12 million years too old to be associated with that event.

The Manicouigan crater has been deeply eroded by the Pleistocene glaciers that scraped the loose sediments off the Canadian shield, pushing them south into the United States. The crater, exposed in bedrock, is currently delineated by two semicircular lakes that are part of a hydroelectric dam project.

The Manicouigan structure has a large central dome, rising 1,640 feet (500 m) above the surrounding surface, culminating at Mount de Babel peak. Manicouigan is characterized by huge amounts of broken, brecciated rocks and shatter cones that point toward the center of the dome. Shatter cones are cone-shaped fractures that form during impacts from the shock wave passing through the adjacent rock, and typically have tips or apexes that point toward the point of impact, but may have more complex patterns that form by the shock waves bouncing off other surfaces in the bedrock.

The Manicouigan crater also has a thick layer of an igneous rock called an impact melt, generated when the force of the impact causes the meteorite and the rock it crashes into to vaporize and melt, and then the melt can fill the resulting crater. The impact melt layer at Manicouigan is more than 325 feet (100 m) thick. There have also been high-pressure mineral phases discovered in the rocks from the Manicouigan structure—phases that form at pressures that could occur only as a result of a meteorite impact and are impossible to reach by other mechanisms at shallow levels of Earth's crust.

Vredefort Impact Structure, South Africa

The Vredefort dome of South Africa is one of the world's largest and oldest known, well-preserved impact structures. Located in the late Archean Witwatersrand basin, the Vredefort dome is a large, multiring structure with a diameter of 87 miles (140 km) formed by the impact of a meteorite 1.97 billion years ago.

The geology and structure of the Vredefort dome is complex, and its origin was the subject of debates for many years. The crater is characterized by a series of concentric rims of rock outcroppings of the different Precambrian rocks in the area, including the Proterozoic Transvaal Supergroup, and the Archean Ventersdorp and Witwatersrand Supergroups, and the underlying Dominion volcanics and Archean granitic basement. Before the impact these rocks formed a shallowly dipping sequence on top of the Archean granitic basement, but the impact was so strong that it excavated a crater. Immediately following, the rocks rebounded, with the Archean basement being uplifted in a steep dome in the center of the crater that rose all the way to the present surface, tilting and folding the surrounding rocks in the process.

The Vredefort dome is famous for hosting a number of geologic features that are diagnostic of meteorite impacts. First, the crater is surrounded by numerous shock metamorphic features, including many impact breccias, some of which are invaded by impact melt glasses called pseudotachylites. Many shatter cones have been identified at Vredefort, and the vast majority of these point inward to a point located just above the present-day surface, presumably pointing to the place of the initial shock and point of impact. Finally, the Vredefort dome is associated with a number of high-pressure mineral phases including coesite, stishovite, and diaplectic silica glass. These features require pressures of about 25, 75–100, and 120 kilobars (equivalent to depths of up 215 miles, or 350 km, depth in Earth), respectively, to form. Since the surrounding rocks did not reach these pressures, the only known way to form these mineral phases is through meteorite impact.

Lunar Impact Craters

The Earth's Moon is the closest celestial object, and it is covered by many impact craters, large and small. The lack of water, crustal recycling through plate tectonics, and weathering as on Earth has preserved craters that are billions of years old, providing scientists with a natural laboratory to observe and model impact craters of different sizes and styles. Thousands on thousands of photographs have revealed the great diversity in styles of lunar craters and have yielded insight into the cratering mechanisms responsible for cratering events on Earth. The large number of impact craters on the Moon also hints at the importance of impact cratering on the early Earth. The Moon has a much lower gravity field than Earth, so Earth has a greater chance of attracting and being hit by any nearby asteroids than the Moon. Since there are so many impact craters on the Moon, there should have been even more on the early Earth. Crustal recycling, erosion, and weathering have simply erased the surface traces of these impacts. Their effects, however, in terms of adding energy, elements, including organic and volatile molecules to Earth, is cumulative, and impacts have played a large role in the evolution of the planet.

NASA missions have also landed on and explored the lunar surface, aiding the understanding of the evolution of the Earth-Moon system, including the materials associated with impact events on the Moon. *Apollo 11,* the first manned lunar mission, launched from the Kennedy Space Center, Florida, via a *Saturn V* launch vehicle on July 16, 1969, and safely returned to Earth on July 24, 1969. The three-man crew aboard the flight consisted of Neil A. Armstrong, commander; Michael Collins, command module pilot; and Edwin E. (Buzz) Aldrin Jr., lunar module pilot. The lunar module (LM), named *Eagle,* carrying astronauts Armstrong and Aldrin, was the first crewed vehicle to land on the Moon. Meanwhile astronaut Collins piloted the command module in a parking orbit around the Moon. Armstrong was the first human ever to stand on the lunar surface, followed by Aldrin. The crew collected 47 pounds of lunar surface material that returned to Earth for analysis. The surface exploration was concluded in 2.5 hours. With the success of *Apollo 11* the national objective to land men on the Moon and return them safely to Earth had been accomplished. The samples collected were distributed to research groups around the country, greatly advancing the understanding of formation and evolution of the Moon.

SUMMARY

Hundreds of meteorite craters have been identified on Earth. Small craters typically have overturned and uplifted rims and a semicircular depression or crater marking the site of the impact. Larger impact craters collapse inward to fill the crater excavated by the impact and develop a characteristic medial high and many rims of uplifted and depressed crustal rocks. Impacts are commonly identified on the basis of impact breccias and shatter cones, by impact melts, and by the presence of high-pressure mineral phases such as coesite, stishovite, and diaplectic glass. Impact craters of all sizes and shapes have been identified on Earth and the Moon.

The most famous and perhaps most consequential impact crater is the one at Chicxulub, on the Yucatán Peninsula of Mexico. Here, a six-mile (10 km) wide meteorite hit Earth 66 million years ago, generating global fires and giant tsunamis, and ejecting tremendous amounts of dust and carbon dioxide into the atmosphere. The result was a mass extinction event at the Cretaceous-Tertiary boundary, and the loss of many species including the dinosaurs.

See also ASTEROID; COMET; MASS EXTINCTIONS; SOLAR SYSTEM.

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Indian geology The subcontinent of India is divided into four main geologic provinces, including two on the Indian peninsula, the mountains in the north, and the Indo-Gangetic Plain between the peninsula and the mountains. Approximately two-thirds of peninsular India consists of Precambrian rocks, including assemblages as old as 3.8 billion years. The Precambrian rocks include granites, high-grade metamorphic granulite terranes, and belts of strongly deformed and metamorphosed sedimentary and volcanic rocks called schist belts (broadly equivalent to greenstone belts of other continents). These Precambrian rocks are covered by thick deposits of lavas known as the Deccan Plateau flood basalts, erupted in the Late Cretaceous and Early Tertiary. The Deccan flood plateau basalts cover large sections of western and central India, especially near Mumbai. The eruption of these flood basalts was a consequence of India's rifting away from other parts of Gondwana as it started its rapid journey to crash into Asia.

Peninsular India contains two converging mountain ranges that run along the east and west coasts and form the east and west boundaries of the Deccan Plateau. The two ranges are joined by the Nilgiri Hills in the south, and the highest point in the ranges is Anai Mudi, with an elevation of 8,841 feet (2,697 m). The Eastern Ghats have an average elevation of 2,000 feet (600 m) and generally lie at 50 to 150 miles (80–240 km) from the Coromandel coastline, and locally form steep cliffs along the coast. The Eastern Ghats are crossed by the Godavari, Krishna, and Kaveri Rivers, and are covered by many hardwood trees. The Western Ghats extend along the Malabar coast from the Tapi River to Cape Comorin at the southern tip of India and are generally very close to the coastline. Elevations in the northern part of the Western Ghats reach 4,000 feet (1,200 m) and 8,652 feet (2,637 m) at Doda Beta in the south. The western side of the Western Ghats receives heavy monsoonal rainfalls, but the eastern side of the Western Ghats is generally dry.

Geologically the Western Ghats extend from the Deccan flood basalt plateau in the north to the Pre-

Satellite image of India *(M-Sat Ltd/Photo Researchers, Inc.)*

cambrian basement shield including the Dharwar craton in the south. Isotopic ages of gneisses and greenstone belts in the Dharwar craton range from 2.6 to 3.4 billion years old. The Dharwar craton is well known for gold deposits associated with greenstone belts and banded-iron formations, with the best-known greenstone belt being the Chitradurga. The Dharwar craton is divided into eastern and western parts by the elongate north-northwest-striking 2.6-billion-year-old Closepet granite, probably of Andean arc affinity. Late Proterozoic metamorphism, locally to granulite grade and including large areas of charnockites, affects much of the southern part of peninsular India. Rocks of the Dharwar craton are overlain by Paleozoic sedimentary deposits of Gondwanan affinity. The Deccan flood basalts erupted at the end of the Cretaceous and overlie Gondwana and continental margin sequences that began developing with the breakup of Gondwana. The Eastern Ghats are entirely within the Precambrian basement rocks of the Indian subcontinent and the Aravalli craton in the north. The Aravalli craton is somewhat younger than the Dharwar craton, with isotopic ages falling in the range of 3.0 billion to 450 million years.

Sedimentary assemblages of peninsular India include many deposited during the Paleozoic and Mesozoic Eras when India was part of the supercontinent of Gondwana; such assemblages are known on the subcontinent as "Gondwanas." These are mostly thin sequences except in some narrow rift valleys and are mostly absent in interior India. In late Mesozoic and Tertiary times postrifting sedimentary assemblages were deposited on the continental margins and are several miles (km) thick in some isolated basins.

The Indo-Gangetic Plain forms a broad, several-hundred-mile (several-hundred-kilometer) wide plain between the Precambrian rocks exposed in southern India, from the active ranges of the Himalayan Mountains in the north. The rocks on the surface of the Indo-Gangetic Plain are very young, and with depth they record the progressive collision of India and Asia, containing the material eroded from the Himalayas as they were thrust upward during the collision. The Precambrian rocks of peninsular India warp downward and dip under the Indo-Gangetic Plain and form the basement for the sediments deposited in the Himalayan foreland basin.

The Himalaya Mountains contain a diverse suite of rocks ranging in age from Precambrian to Tertiary, and most are strongly deformed and metamorphosed from the Tertiary collision of India with Asia. The Main Boundary Thrust dips northward under the Himalayas and separates the deformed mountain ranges from the Indian shield.

PRECAMBRIAN SHIELD OF SOUTHERN INDIA

Southern India consists largely of Precambrian rocks, partly covered by the Deccan flood basalts and thin sedimentary sequences. The shield is made of seven main cratons of Archean age, including the Western Dharwar, Eastern Dharwar, Southern Granulite Terrane, Eastern Ghats, Bhandara, Singhbhum, and Aravalli cratons. Each of these cratons is somewhat different from the others, and most are now joined along intervening thrust belts or wide orogenic belts of intense deformation and metamorphism. In a few cases younger rifts separate the cratons, and the original relationships are unclear. Many of the orogenic belts between the cratons show strong deformation and metamorphism about 1.5 billion years ago, possibly representing the collision of the cratons to form a supercontinent.

Western Dharwar Craton

The Western Dharwar craton is bounded on the west by the Arabian Sea, covered in the north by the Deccan basalts, and separated on the east from the Eastern Dharwar craton by the Closepet granite and a major fault zone along the eastern margin of the Chitradurga schist belt.

Simplified geologic-tectonic map of India. Main Archean terranes are Granulite, Western Dharwar, Eastern Dharwar, Bhandara, Singhbhum, and Aravalli. Other locations on map include Delhi, Patna, Ahmedabad, Calcutta, Nagpur, Mumbai, Hyderabad, Madras, and Bangalore. *(modeled after J. Rogers and S.M. Naqvi, 1987)*

The Western Dharwar craton is the best known of the Archean cratons of India, hosting several large gold deposits in the mafic volcanic/schist belts, especially in the Chitradurga belt. Structures in the Western Dharwar craton, including the main schist belts, strike generally northward, with a broad convex arc facing east toward the Eastern Dharwar craton. Greenstone belts in the northern part of the craton are generally larger and less metamorphosed than those in the south.

Rocks in the Western Dharwar craton are diverse in age and type. The so-called Peninsular Gneiss forms much of the craton and is made up of tonalitic-trondhjemitic gneiss with many inclusions of older sedimentary and igneous rocks. Several generations of igneous dikes and plutons intrude the Peninsular Gneiss, which has yielded isotopic ages of 3.4 to 3.0 billion years, with younger granites intruding the gneiss between 3.0 and 2.9 billion years ago. The term *Dharwar* has been used to describe mafic volcanic and sedimentary schist belts engulfed by quartz-feldspar gneisses of the Peninsular gneiss. There are three main types of mafic rocks included in this general classification: high-grade mafic rocks caught as enclaves in gneisses in the southern part of the craton, coherent belts of amphibolite facies metamorphic grade, and belts preserved at low metamorphic grade. The term *Sargurs* describes the highly deformed greenstone fragments that are generally older than 3.0 billion years. The high-grade schist belts of the Western Dharwar craton contain numerous fragments of ultramafic/mafic layered igneous complexes and include komatiites, basalts, and other magma types. Some of these may be examples of Archean ophiolites, and others may be intrusions into the continental crust. Other rock types include quartzites, conglomerates, greywacke and sandstones, banded-iron formations, mica schists, metamorphosed mafic volcanic rocks, chert, carbonates, and rare layers of evaporites. The 2.3–2.5-billion-year-old Closepet granite on the eastern side of the craton is rich in potassium feldspar, and its highly elongate shape (about 360 miles long by 30 miles wide [600 km by 50 km]) suggests that it may have intruded along a convergent continental margin type of tectonic setting, perhaps during the collision of the Eastern and Western Dharwar cratons.

Most rocks in the Western Dharwar craton are complexly deformed, with layered rocks typically preserving two or three folding generations. Older folds are generally tight to isoclinal, whereas younger folds are more open and upright, and fold interference patterns are common in the older rocks. The cause of the early deformation events in the schist and greenstone belts is not well known, but some of the younger events appear to be related to the collision of the Western Dharwar craton with other blocks, such as the Eastern Dharwar craton and the formation of supercontinents in the Proterozoic.

Eastern Dharwar Craton

The Eastern Dharwar craton is bordered on the west by the Closepet granite and parallel shear zone that separates it from the Western Dharwar craton. This craton has a gradational boundary with the high-grade Southern Granulite terrane in the south. The eastern boundary is a thrust fault that dips under the Eastern Ghats, and the northern boundary is marked by the Godavari rift in some places and is covered by the Deccan basalts in others.

The Eastern Dharwar craton is not as well known as the Western Dharwar and consists of four main rock associations including schist belts, gneiss, granite, and Late Proterozoic basins including the large Cuddapah basin. The most famous schist belt in the Eastern Dharwar craton is the Kolar belt in the south, which is well known for hosting major gold deposits in gold-quartz veins in shear zones. The schist belts consist of metamorphosed volcanic and sedimentary rocks and resemble the schist belts of the Western Dharwar craton. Granites belong to two main suites, including the arcuate bodies that are parallel and similar to the Closepet granite, and a more scattered and diffuse set especially concentrated near Hyderabad. The granites and schist belts are overlain by Proterozoic to Paleozoic sedimentary sequences, which are especially thick in the Cuddapah basin in the east, and in the Bhima basin in the northwest.

Ages of rocks in the Eastern Dharwar craton extend back to 3.01 billion years, with the oldest-known rocks being metasedimentary gneiss near the Closepet granite. Granite gneisses dated 2.95 billion years and Peninsular gneisses dated 2.6 billion years are exposed near Bangalore. The gneisses near the Kolar schist belt in the south are 2.9 billion years old. Mafic dikes with ages around 1.5–1.4 billion years intrude into the Eastern Dharwar craton.

Several kimberlite pipes in the Eastern Dharwar craton may have been the source for diamonds found as detrital grains in conglomerates in the lower part of the Cuddapah basin. The age of the kimberlites is not well established, but estimates span between 1.45 and 1.00 billion years.

The Cuddapah and related Bhima sedimentary basins, as well as the Kaladgi basin on the western Dharwar craton, are not strongly deformed or metamorphosed. The largest of these basins is the Cuddapah, which is preserved in a crescent-shaped structure on the eastern margin of the craton. The age of the lower-most stratum in the Cuddapah basin is 1.6 billion years, and the basin is cut by undeformed mafic dikes with ages of 980 million years. The oldest rock group in the basin is the Cuddapah Group, which is overlain by the Nallamalai Group, then by the Kurnool Group. Almost all of the rocks are mature sediments, including quartz sandstones and conglomerates, and carbonates (limestones and dolostones) that are free of clastic debris. The shales are clay-rich with only rare silty horizons. Most depositional environments are neritic, intertidal, and subaerial, with slightly deeper water facies recorded in eastern strata. Additionally there is a larger percentage of clastic debris in the eastern part of the basin, suggesting that the source was an uplifted orogen to the east, and the basin is a flexural-style foreland basin that records convergence between the Eastern Ghats and the Eastern Dharwar craton in middle Proterozoic times.

Strata in the Cuddapah basin are folded in increasingly tighter and larger folds toward the east, with the fold axes following the curved shape of the basin. Many west-directed thrust faults also cut the strata, and the overall shape and style of the basin are similar to many younger foreland basins and fold-thrust belts. Strata in the basin thicken and are more deformed toward the east. In this model the deformation would have been driven by orogenesis in the middle Proterozoic Eastern Ghats mobile belt that has been faulted against the eastern side of the basin.

Southern Granulite Terrane

The southern tip of the Indian subcontinent comprises the Southern Granulite terrane, a region of complexly and strongly metamorphosed granulite facies gneisses, as well as amphibolite facies gneisses and lower-grade sedimentary sequences. The Southern Granulite terrane is bounded to the north by the Eastern and Western Dharwar cratons.

Rock types in the Southern Granulite terrane are highly unusual and include a suite of metamorphic rocks derived from older sedimentary, volcanic, and gneissic sequences that were subject to very high temperatures and pressures in the presence of carbon dioxide–rich fluids. These conditions formed a suite of rocks that includes the following:

- charnockites, containing orthopyroxene, quartz, K-feldspar, plagioclase, and garnet
- enderbites, containing orthopyroxene, quartz, and plagioclase
- mafic granulite, containing dominantly pyroxene and plagioclase and commonly garnet
- khondalite, containing quartz, sillimanite, garnet, K-feldspar, plagioclase, and graphite
- leptynite, containing quartz, garnet, K-feldspar, plagioclase, amphibole, sillimanite, and biotite
- gneiss, containing quartz, K-feldspar, plagioclase, amphibole, and biotite

These unusual rocks are exposed well in some of the highland areas of southernmost India including the Nilgiri Hills, the Biligirirangan Hills, and the Kodaikanal massif. These exposures are cut by major Proterozoic shear zones including the Achankovil shear zone, the Palghat-Cauvery shear zone, and the Moyar-Bhavani-Attur shear zone. Many of these have been related to different phases of ocean closure and continental movements during the assembly of the Gondwana supercontinent at the end of the Precambrian.

Many if not most of the rocks in the Southern Granulite terrane are Archean, with most ages clustering around 2.6 billion years old, but some rocks are at least 3.0 billion years old. However, the age of the high-grade granulite facies metamorphism is much younger—falling in the range of 700–500 million years. Conditions of metamorphism are estimated to be in the general range of 1,470–1,560°F (800–850°C), at 11–19 miles (18–30 km) depth.

Eastern Ghats Province

The Eastern Ghats province, located east of the Eastern Dharwar craton, consists mainly of high-grade igneous and metamorphic rocks, but the ages of many of the rocks are not well established. The province is elongate in a north-northeast direction, and the main folds and shear zones are generally oriented in this direction as well. The western and northern margin of the Eastern Ghats province is a major thrust fault that places the Eastern Ghats over the Eastern Dharwar craton. This fault, known as the Sukinda thrust, corresponds to major changes in the density of the crust on either side, showing that it is a major structure. The Godavari rift cuts the center of the Eastern Ghats province, then extends across the coastline into the Bay of Bengal.

Rock types in the Eastern Ghats include several igneous suites and high-grade metamorphic rocks. These can be divided into six main rock associations:

- mafic schists, consisting of biotite, muscovite, and amphibole
- charnockites, containing quartz, feldspar, and hyperstene
- khondalites, including calc-silicates that represent strongly metamorphosed sedimentary rocks, and are now rich in garnet, sillimanite, cordierite, and sapphirine
- mafic granulites, containing plagioclase, clinopyroxene, orthopyroxene, and amphibole
- anorthosites, consisting of plagioclase and associated with gabbro, dunite, and chromite bearing serpentinite, some of which have been dated to be about 1.3 billion years old
- alkaline rocks, forming posttectonic plutons cutting the other rocks, some of which have yielded isotopic ages of around 1.3 billion years

All of the rocks in the Eastern Ghats were strongly deformed and metamorphosed in the mid-Proterozoic, around 1.4 billion years ago, and some evidence supports a magmatic event around 1.6 billion years ago. Even though there is a paucity of precisely determined isotopic Archean ages from the Eastern Ghats, many of the rocks, especially the schist belts, are quite similar to rocks in the Eastern and Western Dharwar cratons, and many Indian geologists have suggested that they may likewise be Archean.

Evolution of the Eastern Ghats began with deposition of silty and muddy sediments, carbonates, and basalts that later metamorphosed into khondalites and calc-silicate rocks. Volcano-sedimentary rocks that were deposited in several locations along the western side of the Eastern Ghats were later metamorphosed into schist belts. An orogenic event in the Middle Proterozoic caused east-west shortening and deformed the strata into northeast striking folds and shear zones and was associated with the high-grade granulite facies metamorphism. Later folds reorient some of the older folds, and intrusion of alkaline magmas occurred around 1.3–1.4 billion years ago. Structures along the western margin of the belt and the high-grade metamorphism suggest that the deformation and metamorphism formed during a continent-continent collision. Similarities between the Eastern Ghats and the Southern Granulite terrane suggest that the metamorphic events in the two may be related to the same major continent-continent collision event.

Bhandara Craton

The Bhandara craton is located in the north-central part of the Indian subcontinent, bounded on the east by the Eastern Ghats, the Godavari rift and Deccan basalts on the southwest, the Aravalli craton under the Deccan basalts and younger sediments to the northwest, and the Singhbhum craton to the northeast. The craton consists largely of granites and gneisses with many inclusions of older sedimentary and volcanic rocks, overlain by several Late Proterozoic basins, including the Chhattisgarh and Bastar basins. The groups of volcanic and sedimentary rocks include the Dongargarh, Sakoli, Sausar, Bengpal, Sukma, and Bailadila Groups.

The Satpura orogenic belt cuts east-west across the craton, disrupting the dominantly north-south strike of structures in other parts of the region. The Bhandara craton is known for its rich sedimentary manganese ores that are especially abundant in the Sausar Group.

Granites and gneisses of the Bhandara craton are abundant and intrude older continental shelf-type sediments, although no extensive older continental-type basement has been identified. Some of the gneisses are broadly similar to the peninsular gneisses of the Western Dharwar craton, but their ages have not been determined. Metamorphism of the gneisses occurred at 1.5 billion years ago.

The sedimentary assemblages engulfed in the granites and gneisses include mainly the Dongargarh, Sakoli, and Sausar Assemblages. The Dongargarh Supergroup includes quartz-feldspar-biotite gneisses with minor amounts of basalt, metamorphosed to amphibolite facies in the 2.3-billion-year-old Amgaon Orogeny. Younger rhyolites, sandstones, shales, and tuffaceous rocks are approximately 2.2 billion years old. The Dongargarh Supergroup is intruded by granites dated to be 2.27 billion years old, so the rocks are older than this and likely Early Proterozoic or Archean. Rocks of the Dongargarh Supergroup are deformed by three major fold sets, the first of which produced isoclinal folds in the Amgaon Orogeny, and the second and third of which produced tight folds during the Nandgaon and Khairagarh Orogenies.

The Sakoli Group includes metapelitic rocks disposed in a large, synclinal structure in the western part of the craton. The rocks are metamorphosed to lower amphibolite facies and deformed by an early generation of isoclinal folds and a later group of more open upright folds.

The Sausar Group forms a thin, elongate belt of sandy, shaly, and calcareous metamorphosed sedimentary rocks along the northern part of the craton and is one of the main manganese-producing units in India. The lack of volcanic material in the Sausar Group has made it difficult to determine the age of this sequence, but it is known that the rocks were deformed in the Satpura Orogeny at 1.53 billion years ago. The structural geology of the Sausar Group is interesting and unusual. The southern part of the belt is deformed into isoclinal folds, many of which are overturned and show nappe-style movements toward the north. These are bordered on the north by gneisses of the Tirodi suite and have many inclusions of the sedimentary rocks. This gneissic belt may represent the core of the orogen. To the north in the Satpura Ranges, the rocks are disposed in a series of south-directed nappes and thrust sheets.

Despite much work on the structural geology of the Sausar Group, details of the Satpura orogeny that affected these rocks are vague. The orogeny was a Middle Proterozoic event, with some metamorphic ages of circa 1.5 billion years. The main tectonic transport direction in the orogeny was likely toward the south, although the belt of northward-directed nappes south of the crystalline core of the orogen is enigmatic, and few other orogens show tectonic movement toward the center of the belt. Some fold interference or strike-slip motions in the core of the orogen may have eluded detection.

Singhbhum Craton

The Singhbhum craton is located in eastern India, bounded by the Mahamadi graben and Sukinda thrust fault in the south, the Narmada-Son lineament in the west, the Indo-Gangetic Plain in the north, and the Bay of Bengal in the east. The craton has three main parts: the old Archean Singhbhum nucleus in the south, the 2.2- to 1.0-billion-year-old Singhbhum-Dhalbhum mobile belt north of this, and the Chotanagpur-Satpura belt of gneisses and granites north and west of the mobile belt.

The Singhbum craton comprises many old rocks, including the older metamorphic group that is about 3.2 billion years old. Some evidence points to the possibility of rocks as old as 3.8 billion years in the Singhbum nucleus. Most magmatic activity ended in the Singhbum nucleus by 2.7 billion years ago. These rocks are intruded by granites 2.91–2.95 billion years old and then by diabasic intrusives between 1.5 and 1.0 billion years ago.

The Singhbum craton has three major thrust belts: the Dalma thrust in the northern part of the Singhbum-Dhalbhum mobile belt, the Singhbum thrust between the mobile belt and the Singhbum nucleus, and the Sukinda thrust along the southern margin of the craton. The center of the craton is cut by a major rift valley, filled with Gondwana sediments in the Damodar Valley.

The Singhbum thrust is a 120-mile (200-km) long, bow-shaped belt along the northern side of the Singhbum nucleus. It is more than 15 miles (25 km) wide, and contains at least three main thrust slices. Seismic evidence shows that the structure penetrates the thickness of the lithosphere and is therefore interpreted to be an ancient plate boundary. Blueschist facies rocks, which are high-pressure, low-temperature metamorphic rocks characteristic of younger subduction zone settings but exceedingly rare in Precambrian belts, have reportedly been found along the Singhbum thrust by Indian geologists S. N. Sarkar and A. K. Saha, but other geologists have disputed their finds.

A large part of the Singhbum nucleus consists of the Older Metamorphic Group, preserved as remnants in the intrusive Singhbum Granite complex. These rocks include mica schists, quartzites, calcsilicates, and amphibolites, along with gneissic remnants dated to be 3.8 and 3.2 billion years old. These older metasedimentary rocks are overlain by the Iron Ore Group of shales, hematitic jasper with iron ore layers, mafic lavas, sandstone, and conglomerate, but it is not clear which group is older. The iron ore deposits show three periods of folding, including F1 reclined folds, and F2 and F3 upright folds that interact to form fold interference patterns.

The Singhbum-Dhalbhum mobile belt includes rocks of the Singhbum Group, including mica schists, hornblende schists, quartzose schists, granulites, chloritic schists, and amphibolites. Rocks north of the Singhbum thrust are disposed in a large anticlinorium, then farther north they form a synclinorium containing ophiolitic-type volcanic and plutonic rocks of the Dalma Group in its uppermost sections. The rocks show up to four folding generations including early subhorizontal recumbent folds, followed by two generations of upright folds. The fourth generation of folds is associated with the shear zones in the south, related to the formation of the large Singhbum thrust. The Chotanagpur terrain north of the mobile belt contains a large area of gneissic and granitic rocks but also includes metasedimentary rocks, granulites, mafic/ultramafic schists, and anorthosites, and may represent a continental fragment or an island arc terrane.

Rocks in the Singhbum-Dhalbhum mobile belt are interpreted as a Proterozoic orogen deformed at 1.6 billion years ago. These rocks include shallow water sedimentary sequences overthrust by oceanic and ophiolitic assemblages preserved as structurally bounded mafic/ultramafic sequences during closure of a Proterozoic ocean. The ophiolite belt is succeeded southward by a flysch belt, a fold-thrust belt, then a molasse basin on the older Singhbum cratonic nucleus. The rocks were transported from north to south over the Singhbum granite, which represents the foreland to the orogen. The hinterland, or internal parts of the orogen, is in the Chotanagpur area, and the orogen represents the collision of the Chotanagpur block with the Singhbum nucleus about 1.6 billion years ago.

Aravalli Craton

The Aravalli craton is located in the northwestern part of peninsular India, bounded on the north by the Himalaya Mountain chain, the Cambay graben in the southwest, and the Narmada-Son lineament on the south and southeast. Young sediments cover the western boundary and may extend farther into Pakistan.

Rocks of the Aravalli craton are quite different from the Dharwar and other cratons of the Indian shield. They consist mostly of Proterozoic phyllites, graywackes, quartzites, and carbonates, with minor mafic and ultramafic schists. Stromatolites are common in the carbonates and are associated with phosphorite deposits. Banded-iron formations are almost totally absent from the Aravalli craton but common in other cratonic blocks of the Indian shield.

Major structures of the Aravalli craton include the Great Boundary fault on the eastern edge of the Aravalli-Delhi belt, the Delhi-Haridwar ridge, and the Faizabad ridge, which is an extension of the Bundelkhand massif under the Indo-Gangetic Plain. The Aravalli-Delhi belt contains a large number of granitic rocks emplaced over a wide range of time from 3.5 billion to 750 million years ago.

The oldest rocks of the Aravalli craton are found as metasedimentary/metavolcanic inclusions, named the Bhilwara suite, in the Banded Gneiss complex. The gneisses include metasedimentary units, migmatites, granitic gneisses and pegmatites, and metabasic layers. The Bhilwara suite is preserved in several elongate belts within the Banded Gneiss complex, especially between Karera and the Great Boundary fault. Rock types include shales, slates, quartzites, dolostones, marbles, cherts, graywackes, and hornblende and mica-schists. Sedimentary structures in these rocks suggest that they were deposited in a shallow shelf platformal environment.

The Aravalli Supergroup unconformably overlies this Banded Gneiss complex in some places but is intruded by the gneissic rocks in others. These conflicting relationships show that the Banded Gneiss complex consists of several different units that still need additional work to separate them from one another, as confirmed by a range of isotopic ages on the gneisses that extends from 3.5 to 2.0 billion years. Rock types in the Aravalli Supergroup, including quartzites, greywacke, and carbonates, have experienced greenschist facies metamorphism and are intruded by pre-, syn-, and posttectonic granitoids and mafic-ultramafic suites. Ages of the Aravalli Supergroup range between 2.5 and 2.0 billion years. The Aravalli Supergroup is complexly folded by as many as four generations, including early reclined, typically rootless folds, followed by later generations of folds distorting the outcrop belts into hook-shaped synclines, anticlines, and more complex shapes.

The Delhi Supergroup apparently overlies the Aravalli Supergroup, and parts of it are at least 1.6 billion years old, though other sections may be significantly younger. The Delhi Supergroup is the main rock suite outcropping in the Aravalli Mountains, over a distance of more than 350 miles (700 km) from Gujarat to Delhi. The Delhi Supergroup includes quartzites, conglomerates, arkoses, phyllites, slates, limestones, marbles, mafic volcanic rocks, and amphibolites. The rocks are complexly deformed and metamorphosed between greenschist and granulite grades. Two main deformation events are recognized from structures in the Delhi Supergroup. The first deformation event produced isoclinal folds with axial planar foliation parallel to bedding surfaces, whereas the second produced open to tight asymmetrical folds that plunge north to north-northwest.

Exposures of rock are few and far between in the Bundelkhand area, but the rocks there include granites and gneisses deposited over a considerable time spanning much of the Precambrian. The northeastern part of the craton is overlain by generally flat-lying rocks of the Late Proterozoic Vindhyan Supergroup, deformed only near the Great Boundary fault and in the south near the Satpura orogen. Vindhyan sedimentary rocks include basal conglomerates and quartzite, and grades up into quartz arenite, and higher in the section into limestones, shales, and other shallow-water sedimentary deposits. The upper part of the Vindhyan Supergroup includes sandstones and conglomerates, and some have diamonds probably eroded from nearby kimberlite pipes.

The Arvalli craton hosts a few alkaline igneous intrusions and kimberlite pipes. The alkaline rocks were emplaced around 1.5 billion years ago, and the kimberlites have yielded a variety of isotopic ages ranging from 1.63 to 1.12 billion years, all with large uncertainties.

HIMALAYA MOUNTAINS

The Himalaya Mountains were formed during the Tertiary continent-continent collision between India and Asia and contain the tallest mountains, as well as those exhibiting the greatest vertical relief over short distances, in the world. The range extends for more than 1,800 miles (3,000 km) from the Karakoram near Kabul, Afghanistan, past Lhasa, Tibet, to Arunachal Pradesh in the remote Assam Province of India. Ten of the world's 14 peaks that rise to more than 26,000 feet (8,000 m) are located in the Himalayas, including Mount Everest, 29,035 feet (8,850 m), Nanga Parbat, 26,650 feet (8,123 m), and Namche Barwa, 25,440 feet (7,754 m). The rivers that drain the Himalayas exhibit some of the highest sediment outputs in the world, including the Indus, Ganges, and Brahmaputra. The Indo-Gangetic Plain, on the southern side of the Himalayas, is a foreland basin filled by sediments eroded from the mountains and deposited on Precambrian and Gondwanan rocks of peninsular India. The northern margin of the Himalayas is marked by the world's highest and largest uplifted plateau, the Tibetan Plateau.

The Himalayas is one of the youngest mountain ranges in the world but has a long and complicated history best understood in the context of five main structural and tectonic units within the ranges. The Subhimalaya includes the Neogene Siwalik molasse, bounded on the south by the Main Frontal Thrust that places the Siwalik molasse over the Indo-Gangetic Plain. The Lower or Subhimalaya is thrust over the Subhimalaya along the Main Boundary Thrust, and consists mainly of deformed thrust sheets derived from the northern margin of the Indian shield. The High Himalaya is a large area of crystalline basement rocks, thrust over the Subhimalaya along the Main Central Thrust. Farther north, the High Himalaya sedimentary series or Tibetan Himalaya consists of sedimentary rocks deposited on the crystalline

Simplified map of the Himalaya Mountains and surrounding areas, showing main tectonic zones and faults and Cenozoic-Quaternary basins. The Indus-Tsangpo suture is located along the boundary between the Transhimalaya and the Himalayas. Names are as follows: Ch F, Chaman faults; DeN, Dacht-e-Newar; E, Everest (29,015 feet [8,846 m]); H, Hazara; I, Islamabad; K, Kathmandu; Ka, Kashmir; Kb, Kabul; Ki, Karachi; Ko, Kohistan; Ks, Kailas; NB, Namche Barwa; NP, Nanga Parbat (26,650 feet or 8,125 m); P, Peshawar; Pk, Pokhra; Q, Quetta; T, Thakkhola; US, Upper Sutlej.

basement of the High Himalaya. Finally, the Indus-Tsangpo suture is the suture between the Himalayas and the Tibetan Plateau to the north.

Sedimentary rocks in the Himalayas record events on the Indian subcontinent, including a thick Cambrian-Ordovician through Late Carboniferous/Early Permian Gondwanan sequence, followed by rocks deposited during rifting and subsidence events on the margins of the Tethys and Neotethys Oceans. The collision of India with Asia was in progress by the Early Eocene. This collision exposed the diverse rocks in the Himalayas, revealing a rich geologic history that extends back to the Precambrian, where shield rocks of the Aravalli and Delhi cratons are intruded by 500-million-year-old granites. Subduction of Tethyan oceanic crust along the southern margin of Tibet formed an Andean-style arc represented by the Trans-Himalaya batholith that extends west into the Kohistan island arc sequence. The obduction of ophiolites and high-pressure (blueschist facies) metamorphism dated to have occurred around 100 million years ago is believed to be related to this subduction. Thrust stacks began stacking up on the Indian subcontinent, and by the Miocene attempted deep intracrustal subduction of the Indian plate beneath Tibet along the Main Central Thrust formed high-grade metamorphism and generated a suite of granitic rocks in the Himalayas. After 15–10 million years ago movements were transferred to the south to the Main Frontal Thrust, which is still active.

INDO-GANGETIC PLAIN

The Indo-Gangetic Plain is the active foreland basin of the India-Asia collision, with sediments derived from erosion of the Himalaya Mountains and carried by numerous rivers that feed into the Indus and Ganges Rivers. Alluvial deposits of the Indo-Gangetic Plain stretch from the Indus River in Pakistan to the Punjab Plain in India and Pakistan, to the Haryana Plain and Ganges delta in Bangladesh. Sediments in the foreland basin extend up to 24,500 feet (7,500 m) thick over the basement rocks of the Indian shield, thinning toward the southern boundary of the basin plain. The plain has very little relief, with only occasional bluffs and terraces related to changes in river levels.

The northern boundary of the plain is marked by two narrow belts known as Terai, containing small hills formed by coarse remnant gravel deposits emerging from mountain streams. Many springs emanate from these gravel deposits forming large, swampy areas along the major rivers. In most places the Indo-Gangetic Plain is about 250 miles (400 km) wide. The southern boundary of the plains is marked by the front of the Great Indian Desert in Rajasthan, then continues eastward to the Bay of Bengal along the hills of the Central Highlands.

The Indo-Gangetic Plain can be divided into three geographically and hydrologically distinct sections. The Indus Valley in the west is fed by the Indus River, which flows out of Kashmir, the Hundu Kush, and the Karakoram range. The Punjab and Haryana Plains are fed by runoff from the Siwalik and Himalaya Mountains into the Ganges River, and fed by the Lower Ganga and Brahmaputra drainage systems in the east. The lower Ganga plains and Assam Valley are lush and heavily vegetated, and the waters flow into the deltaic regions of Bangladesh.

Clastic sediments of the foreland basin deposits under the Indo-Gangetic plain Eocene-Oligocene (about 50–30 million-year old) deposits, grading up to the Miocene to Pleistocene Siwalik clastic rocks, eroded from the Siwalik and Himalaya ranges. The basement of the Indian shield dips about 15° beneath the Great Boundary and other faults marking the deformation front at the toe of the Himalayas.

See also ARCHEAN; CONVERGENT PLATE MARGIN PROCESSES; CRATON; GONDWANA, GONDWANALAND; GREENSTONE BELTS; LARGE IGNEOUS PROVINCES, FLOOD BASALT.

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interstellar medium The interstellar medium, which consists of the areas or voids between the stars and galaxies, represents a nearly perfect vacuum, with a density a trillion trillion times less than that of typical stars. The density of the interstellar medium is so low that there are only a couple of atoms per cubic inch (about 1 atom per cubic cm), or roughly a thimbleful of atoms in a volume the size of the Earth. Interstellar matter includes all of the gas, dust, dark matter, and other material in the universe not contained within stars, galaxies, or galaxy clusters. Despite the extremely low density of the interstellar medium, the vast size of the space is such that the amount of matter in the interstellar medium is about the same as that in all of the stars and galaxies.

Matter in the interstellar medium consists of two main components—gas and dust. In many places in the universe dust forms dark clouds of gigantic size that obscure distant light from passing through, making parts of the universe appear dark. This dust consists of clumps of atoms and molecules whose sizes are comparable to the wavelength of light (10^{-7} m), and much larger than the interstellar gas. The size of the dust particles explains why dust clouds appear dark. Electromagnetic radiation, such as visible light, can be effectively blocked only by particles of similar or greater size than the wavelength of the incident light (or other radiation), and since the size of the dust is similar to the wavelength of light, dust is an excellent blocker of light and appears dark, blocking light from sources behind the dust clouds. However, longer-wavelength radio waves can pass through dust clouds unimpeded. Gas in the interstellar medium is composed mainly of individual atoms of about 1 angstrom (10^{-10} m) in size, and a smaller amount of atoms combined into molecules. The size of the interstellar gas is less than the wavelengths of electromagnetic radiation in most of the visible and radio wavelengths, so this radiation, including light, can pass through the gas, with absorption occurring within a specific narrow range of wavelengths. Interstellar dust, however, blocks the shorter wavelength optical, ultraviolet, and X-ray radiation.

The gas and dust in the interstellar medium preferentially absorbs the longer wavelengths of light from the higher-frequency blue area of the spectrum, so stars and galaxies appear redder than they actually are. Despite this "reddening" of the appearance of stars, the spectral signature, and absorption lines in the stars' spectrums, are mostly unaffected by interstellar dust. With this relationship it is possible to measure the spectrum of a star, which will reveal its luminosity and color. Then by measuring the color on Earth, the amount of reddening by interaction with dust in the interstellar medium can be measured, and this in turn reveals information about the amount and type of interstellar dust the light encountered on its transit from the star to Earth.

Interstellar space is quite cold, with an average temperature of about 100 kelvin (which is -173°C, or -279°F), but ranging from a few kelvins (near absolute zero, where all motion of atoms stops) to several hundred kelvin near stars and other sources of radiation.

Cone Nebula pillar of gas and dust. Photo taken by Advanced Camera for Surveys aboard *Hubble* during space shuttle *STS-109* mission in March 2002 *(NASA, H. Ford (JHU), G. Illingworth (USCS/LO), M. Clampin (STScI), G. Hartig (STScI), the ACS Science Team, and ESA)*

Interstellar gas is made mostly (about 90 percent) of atomic and molecular hydrogen, followed by about 9 percent helium, and 1 percent heavier elements such as carbon, oxygen, silicon, and iron, but the heavier elements have a much lower concentration in the interstellar gas than in stars or in the Earth's solar system. This may be because the heavier elements were combined into molecules to form interstellar dust, whose composition is not well known. Dust is known to include these heavier elements such as silicon, iron, and graphite, as well as ices of water, ammonia, and methane, similar to the "dirty ice" found in comet nuclei. Interstellar dust polarizes light that passes through it; in other words it aligns the light so that the electromagnetic radiation vibrates in a single plane instead of randomly as in unpolarized light. The light becomes polarized because the interstellar dust is made of long, skinny needlelike particles aligned in a specific direction. The cause of this alignment of interstellar dust is the subject of much research and debate but is thought to be caused by the dust particles aligning themselves along weak magnetic field lines in interstellar space.

NEBULAE

Nebulae are areas of interstellar space that appear fuzzy yet are clearly distinguishable from surrounding areas of space, and many of those visible from Earth are concentrated in the plane of the Milky Way Galaxy. Many nebulae are clouds of interstellar gas and dust. In some cases these clouds block the light of stars that are located behind (from the observer's point of view) the nebula, and in other cases the nebulae appear bright and are lit up from the inside, typically by groups of young hot stars. Bright nebulae are known as emission nebulae, being hot glowing clouds of ionized interstellar gas. These nebulae have hot young stars in their centers that emit huge amounts of ultraviolet radiation, which in turn ionizes the surrounding gas, causing the spectacular glow of the clouds visible from Earth. Emission nebulae have red colors because the ionized hydrogen atoms in the gas clouds emit light in the red part of the visible spectrum, and hydrogen is the most abundant gas in the clouds. Other gases, such as helium, may lace the nebulae with other colors, and dark bands wisping across the nebulae are dust clouds that are integral parts of the nebulae. The gases in the nebulae emit spectra when ionized, and these spectra can reveal information about the composition of the gases in the nebulae. Most are made of 90 percent hydrogen, 9 percent helium, and 1 percent heavier elements, similar to the composition of interstellar gas. Nebulae have temperatures measured at around 8,000 kelvin (7,727°C, or 13,940°F), masses of about a couple of hundred to several thousand solar masses, and densities of several hundred to a thousand particles per cubic inch (a few hundred particles per cubic cm, or 8-10 × 10^7 particles per m^3).

Some emission nebulae have areas with green-colored glowing gases, known to be caused by doubly ionized oxygen atoms. These oxygen atoms contain electrons that exist in a raised level of energy and if undisturbed for several hours (without experiencing collisions with other particles) emit a photon, in the green wavelengths, when they drop down to the normal ionized state.

DUST CLOUDS

Dark areas of the sky can be voids, or alternatively, areas where the light is obscured by cold and relatively dense clouds of dust particles. They typically appear as dark, irregular areas in otherwise starlight areas of the sky. Dark dust clouds are typically about 100 kelvin (equivalent to -173°C, or -279°F), but can be considerably colder, range in size from bigger than Earth's solar system to many parsecs across, and have densities thousands to millions of times greater than surrounding voids in space. These dust clouds are composed predominantly of gas, but the property of absorbing light from stars is due primarily to the dust within the clouds.

Information about dust clouds can be learned from their characteristic absorption spectra, which can reveal details about the composition, temperature, and density of the dust cloud. As light leaves a star, the spectra will have the characteristic spectrum from the temperature and elements of that star, and if the light passes through a dust cloud, the spectrum of the dust will be added to that from the star. The cooler the temperature of the dust, the thinner the spectral absorption lines, so the spectral lines of the dust are easily distinguished from those of the original star from which the light arose. Spectral lines from dust clouds have revealed that most have compositions that are virtually identical to other parts of space, characterized by mostly (about 90 percent) atomic and molecular hydrogen, followed by about 9 percent helium, and followed by 1 percent heavier elements such as carbon, oxygen, silicon, and iron.

Although dark dust clouds do not emit light, since they are too cold and composed of neutral atoms and molecules, they do emit at longer wavelengths such as in the infrared. Interstellar matter also emits radiation with a wavelength of 8.2 inches (21 cm), caused by the emission of a low-energy photon when hydrogen changes from a relatively high-energy configuration, with the sense of spin of the atom's electron and proton being the same, to a lower energy configuration, in which the electron and proton have opposite senses of spin. Detection of the characteristic 8.2-inch (21-cm) radio wave radiation has enabled regions of the universe that contain enough hydrogen to emit these photons to be mapped and studied in terms of their temperature, density, composition, and velocity. The radio waves have a wavelength much larger than any interstellar dust particles, which means that the dust in interstellar space does not absorb the energy of or interfere with the 8.2-inch (21-cm) radiation, and it can be measured and studied undisturbed from Earth.

MOLECULAR CLOUDS

Molecular clouds are among the largest structures of interstellar space. They consist of cold and relatively dense (10^{12} particles/cm^3) collections of matter in molecular form. Molecules in these clouds can become excited by collision with other particles or by interacting with radiation. When either happens, the molecules reach a higher energy state when they are excited, and when they relax to a lower energy state, they emit a photon that can then be detected by astronomers. Molecules are more complex than atoms, so they can produce a greater variety of energy released during changes in rotation, electron transitions, and vibrations, each releasing a characteristic photon emission. Most molecular clouds are located in very dusty and dense areas in interstellar space, so energy released in these processes in the ultraviolet, optical, and most infrared wavelengths is absorbed by the local dust clouds, but photons and energy released at radio-wave frequencies moves through this medium and can be detected from Earth.

Spectra from molecular clouds reveal that they consist mostly of molecular hydrogen (H_2), but molecular hydrogen does not emit or absorb radio wave radiation, so it is not useful as a probe. But the spectra emitted from other molecules have proven useful for studying molecular clouds. Some of the most useful include carbon monoxide, hydrogen cyanide, ammonia, water, methyl alcohol, and formaldehyde, and many dozens of other complex molecules. These molecules are used as tracers of the physical and chemical makeup of the molecular clouds and are interpreted to have formed in the clouds. The spectral lines from molecular clouds can also be used to determine the composition of the clouds, their temperature, density, and distribution. One of the major discoveries about molecular clouds made in the past few decades is that the clouds are not isolated bodies, but form giant molecular cloud complexes, as large as 50 parsecs across, each containing millions of stars. The Milky Way Galaxy alone has more than 1,000 known molecular clouds.

See also ASTROPHYSICS; CONSTELLATION; COSMOLOGY; GALAXIES.

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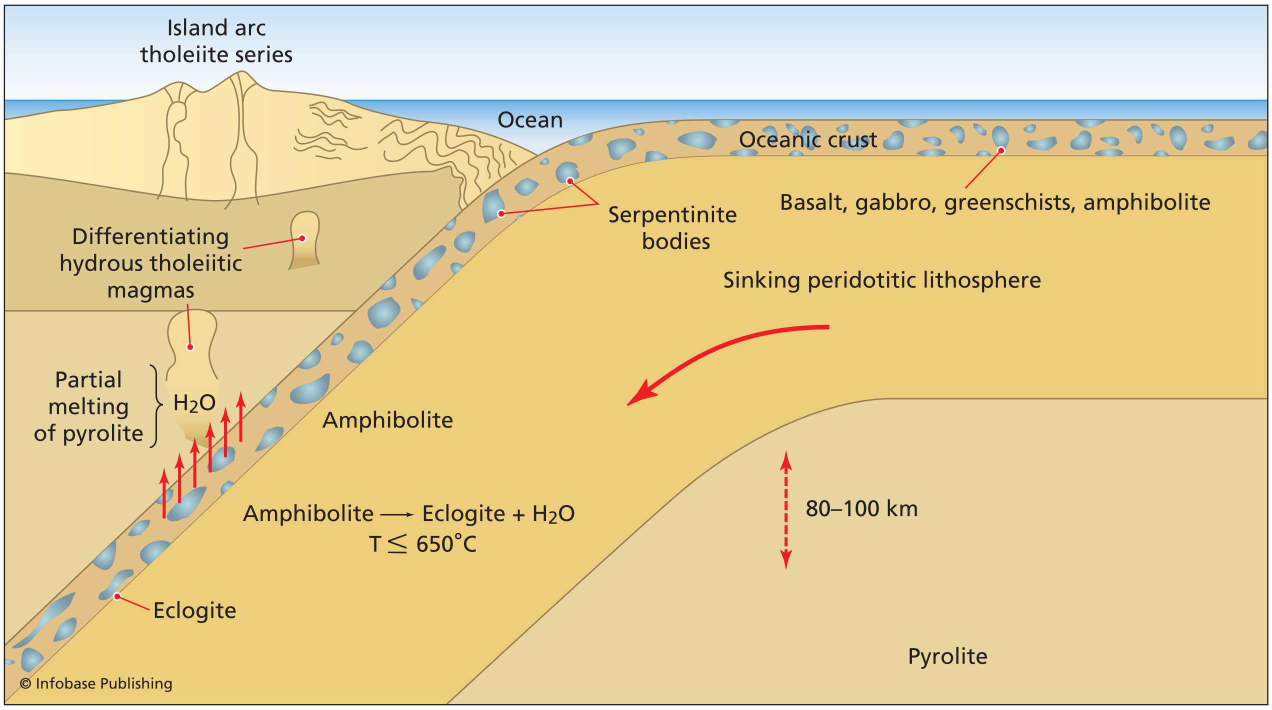
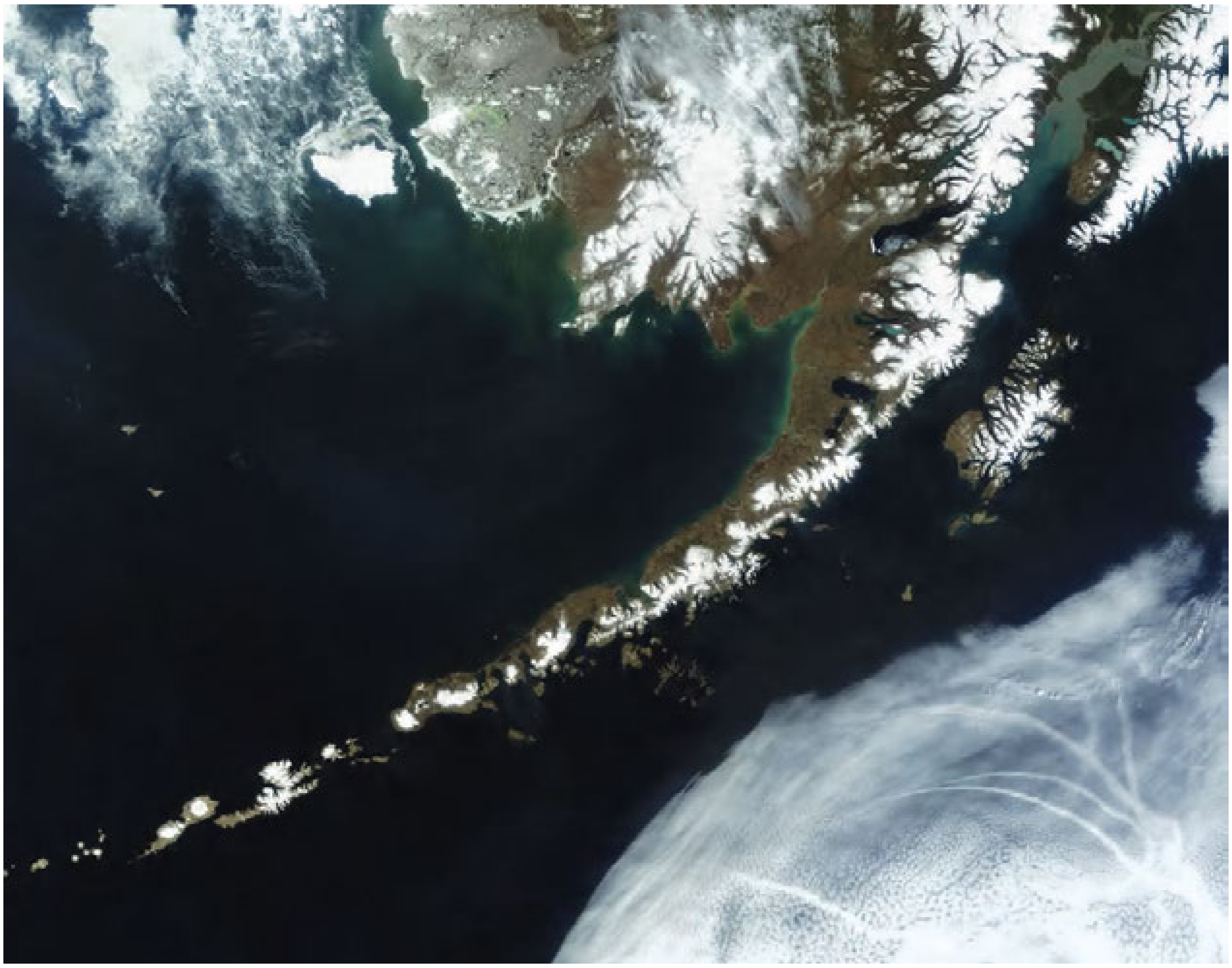
island arcs, historical eruptions Island arcs are belts of high seismic activity and high heat flow with chains of active volcanoes, bordered by a submarine trench formed at a subduction zone. They form where plates of oceanic lithosphere are subducted beneath another oceanic plate, and the down-going oceanic lithosphere may be subducted to 500 miles (700 km) or more. A related type of volcanic arc, an Andean or continental-margin volcanic arc, forms on the edge of a continental plate where an oceanic slab is subducted beneath the edge of the continent. In both types of arcs fluids forced out of the subducting slab at 60–100 miles' depth (100–160 km) cause the mantle above the subducting slab to melt partially, and these magmas migrate upward to form the island or continental margin arc. In most cases these arcs are located 90–120 miles (150–200 km) from the trench, with the distance determined by the dip of the down-going slab.

Volcanic arcs developed above subduction zones have several different geomorphic zones defined largely on their topographic and structural expressions. The active arc is the topographic high with volcanoes, and the back arc region stretches from the active arc away from the trench; it may end in an older rifted arc or continent. The arc is succeeded seaward by the fore-arc basin, a generally flat topographic basin with shallow- to deep-water sediments, typically deposited over older accreted sediments and ophiolitic or continental basement. The accretionary prism includes uplifted, strongly deformed rocks scraped off the downgoing oceanic plate on a series of faults that branch off from the subduction zone thrust fault. Some accretionary prisms are 50–100 miles (80–160 km) wide, and can be thousands of miles long. The world's largest accretionary prisms currently extend around the Pacific Ocean rim, including the southern Alaska accretionary prism, the Franciscan complex in California, and prisms in Japan and the southwest Pacific. The trench may be several to five or more miles (10 km) deep below the average level of the seafloor in the region and marks the boundary between the overriding and underthrusting plates. The outer trench slope is the region from the trench to the top of the flexed oceanic crust that forms a few hundred-meter-high topographic rise known as the forebulge on the down-going plate.

Trench depressions are triangular shaped in profile and typically partly to completely filled with graywacke-shale sediments derived from erosion of the accretionary wedge, and deposited by sediment-laden, fast-moving, down-slope flows known as turbidity currents. The resulting sedimentary rock types have a characteristic style of layering and an upward decrease in grain size, and are known as turbidites. Turbidites may also be transported by currents along the trench axis for large distances, up to hundreds or even thousands of miles from their ultimate source in uplifted mountains in the convergent plate boundary orogen. *Flysch* is a term that applies to rapidly deposited deep marine syn-orogenic clastic rocks that are generally turbidites. Chaotic deposits known as olistostromes that typically have clasts or blocks of one rock type, such as limestone or sandstone, mixed with a muddy or shaly matrix also characterize trenches. These are interpreted as slump or giant submarine landslide deposits. They are common in trenches because of the oversteepening of slopes in the wedge. Sediments that get accreted may also include pelagic (deep-water) sediments initially deposited on the subducting plate, such as red clay,



Cross section of island arc showing the physiography and geologic processes involved during subduction and formation of the arc



Terra MODIS satellite image of Aleutian Islands in Alaska, May 25, 2006 *(Jeff Schmaltz/NASA/Visible Earth)*

siliceous ooze, chert, manganiferous chert, calcareous ooze, and windblown dust.

The sediments are deposited as flat-lying turbidite packages, then are gradually incorporated into the accretionary wedge complex through folding and the propagation of faults through the trench sediments. Subduction accretion accretes sediments deposited on the underriding plate onto the base of the overriding plate. It causes the rotation and uplift of the accretionary prism, a broadly steady process that continues as long as sediment-laden trench deposits are thrust deeper into the trench. New faults will typically form and propagate beneath older ones, rotating the old faults and structures to steeper attitudes as new material is added to the toe and base of the accretionary wedge. This process increases the size of the overriding accretionary wedge and causes a seaward-younging in the age of deformation.

Parts of the oceanic basement to the subducting slab are sometimes scraped off and incorporated into the accretionary prisms. These tectonic slivers typically consist of fault-bounded slices of basalt, gabbro, and ultramafic rocks; rarely, partial or even complete ophiolite sequences can be recognized. These ophiolitic slivers are often parts of highly deformed belts of rock known as mélanges. Mélanges are mixtures of many different rock types typically including blocks of oceanic basement or limestone in muddy, shaly, serpentinitic, or even a cherty matrix. Mélanges are formed by tectonic mixing of the many different types of rocks found in the fore arc, and are one of the hallmarks of convergent boundaries.

TYPES OF ISLAND AND CONVERGENT MARGIN ARCS

There are major differences in processes that occur at continental or Andean-style versus oceanic or island arc systems, also known as Marianas-type arcs. Andean-type arcs have shallow trenches, fewer than four miles (6 km) deep, whereas Marianas-type arcs typically have deep trenches reaching seven miles (11 km) in depth. Most Andean-type arcs subduct young oceanic crust and have very shallow-dipping subduction zones, whereas Marianas-type arcs subduct old oceanic crust and have steeply dipping zones of high earthquake activity, called Benioff zones, marking the top of the subducting slab. Andean arcs have back-arc regions dominated by foreland (retroarc) fold-thrust belts and sedimentary basins, whereas Marianas-type arcs typically have back-arc basins, often with active seafloor spreading. Andean arcs have thick crust, up to 45 miles (70 km) thick, and big earthquakes in the overriding plate, while Marianas-type arcs have thin crust, typically only 12 miles (20 km) thick, and have big earthquakes in the underriding plate. Andean arcs have only rare volcanoes, and these have magmas rich in SiO_2 such as rhyolites and andesites. Plutonic rocks are more common, and the basement is continental crust. Marianas-type arcs have many volcanoes that erupt lava low in silica content, typically basalt, and are built on oceanic crust.

Many arcs are transitional between the Andean or continental-margin types and the oceanic or Marianas-types, and some arcs have large amounts of strike-slip motion. The causes of these variations have been investigated, and it has been determined that the rate of convergence has little effect, but the relative motion directions and the age of the subducted oceanic crust seem to have the biggest effects. In particular, old oceanic crust tends to sink to the point where it has a near-vertical dip, rolling back through the viscous mantle, and dragging the arc and forearc regions of overlying Marianas-type arcs with it. This process contributes to the formation of back-arc basins.

As the cold subducting slab is pushed into the mantle, it cools the surrounding mantle and forearc. Therefore, the effects of the downgoing slab dominate the thermal and fluid structure of arcs. Fluids released from the slab as it descends past 70 miles (110 km) aid partial melting in the overlying mantle and form the magmas that form the arc on the overriding plate. This broad thermal structure of arcs results in the formation of paired metamorphic belts, where the metamorphism in the trench environment grades from cold and low-pressure at the surface to cold and high-pressure at depth, whereas the arc records low and high-pressure, high-temperature metamorphic facies series. One of the distinctive rock associations of trench environments is the formation of the unusual high-pressure, low-temperature blueschist facies rocks in subduction zones. The presence of index minerals glaucophane (a sodic amphibole), jadeite (a sodic pyroxene), and lawsonite (Ca-zeolite) indicate low temperatures extended to depths near 20 miles (20–30 km) (7–10 kbar). Since these minerals are unstable at high temperatures, their presence indicates they formed in a low-temperature environment, and the cooling effects of the subducting plate offer the only known environment to maintain such cool temperatures at depth in the Earth.

Fore-arc basins may include several-mile (or kilometer) thick accumulations of sediments deposited in response to subsidence induced by tectonic loading or thermal cooling of fore arcs built on oceanic lithosphere. The Great Valley of California is a fore-arc basin formed on oceanic fore-arc crust preserved in ophiolitic fragments found in central California; Cook Inlet, Alaska, is an active fore-arc basin formed in front of the Aleutian and Alaska range volcanic arc.

The rocks in the active arcs typically include several different facies. Volcanic rocks may include subaerial flows, tuffs, welded tuffs, volcaniclastic conglomerate, sandstone, and pelagic rocks. Debris flows from volcanic flanks are common, and there may be abundant and thick accumulations of ash deposited by winds and dropped by Plinian and other eruption columns. Volcanic rocks in arcs include mainly calc-alkaline series, showing early iron enrichment in the melt, typically including basalts, andesites, dacites, and rhyolites. Immature island arcs are strongly biased toward eruption at the mafic end of the spectrum, and may also include tholeiitic basalts, picrites (a magnesium-rich basalt), and other volcanic and intrusive series. More mature continental arcs erupt more felsic rocks and may include large caldera complexes.

Back-arc or marginal basins form behind extensional arcs, or may include pieces of oceanic crust trapped by the formation of a new arc on the edge of an oceanic plate. Many extensional back arcs are found in the southwest Pacific, whereas the Bering Sea, between Alaska and Kamchatka, is thought to be a piece of oceanic crust trapped during the formation of the Aleutian chain. Extensional back-arc basins may have oceanic crust generated by seafloor spreading, and these systems very much resemble the spreading centers found at divergent plate boundaries. The geochemical signature of some of the lavas, however, shows some subtle and some not-so-subtle differences, with water and volatiles being more important in the generation of magmas in back-arc suprasubduction zone environments.

Compressional arcs such as the Andes have tall mountains, reaching heights of more than 24,000 feet (7,315 m) over broad areas. They have rare or no volcanism but much plutonism, and typically have shallow dipping slabs beneath them. They have thick continental crust with large compressional earthquakes, and show a foreland-style retro-arc basin in the back-arc region. Some compressional arc segments do not have accretionary forearcs but exhibit subduction erosion during which material is eroded and scraped off the overriding plate, and dragged down into the subduction zone. The Andes show remarkable along-strike variations in processes and tectonic style, with sharp boundaries between different segments. These variations seem to be related to what is being subducted and plate motion vectors. In areas where the down-going slab has steep dips the overriding plate has volcanic rocks; in areas of shallow subduction there is no volcanism.

TYPES OF VOLCANISM IN DIFFERENT ARCS

The most essential part of an island arc is the volcanic center, consisting of a line of volcanic islands comprising volcanic and pyroclastic debris, forming a linear chain about 60–70 miles (100–110 km) above the subducting slab. In island arcs the volcanic rocks are generally of several different types called volcanic series. These include a tholeiitic series, consisting of tholeiitic basalt, andesite, and less common dacite. The calc-alkaline series has basalts rich in alumina, abundant andesite, dacite, and some rhyolite. A third series, the alkali series, includes a sodic group dominated by alkali olivine basalt, alkalic andesite, trachyite, and alkalic rhyolite. A rarer assemblage of volcanic rocks consists of the shoshonite group, comprising of shoshonite, latite, and leucite-bearing magmatic rocks.

The magmatic rocks in island and continental-margin arcs are built on a basement or substrate made of older oceanic crust, or on the edge of a continent. Some arcs change along strike, being built on the edge of a continent in one location and extending off into the ocean, such as the Aleutians, which are built on North American basement in the east and extend to an oceanic island arc in the west. A similar transition exists in the arc system in Indonesia that extends from Bali to West Papua (Irian Jaya) to Sumatra. There is a general correlation between the type of magma that erupts in arc and the type of underlying crust. Arcs built on oceanic crust are dominated by tholeiitic-type volcanic series, whereas arcs built on thicker continental basement are more evolved and have more of the calc-alkaline and shoshonitic series erupted in their volcanic centers.

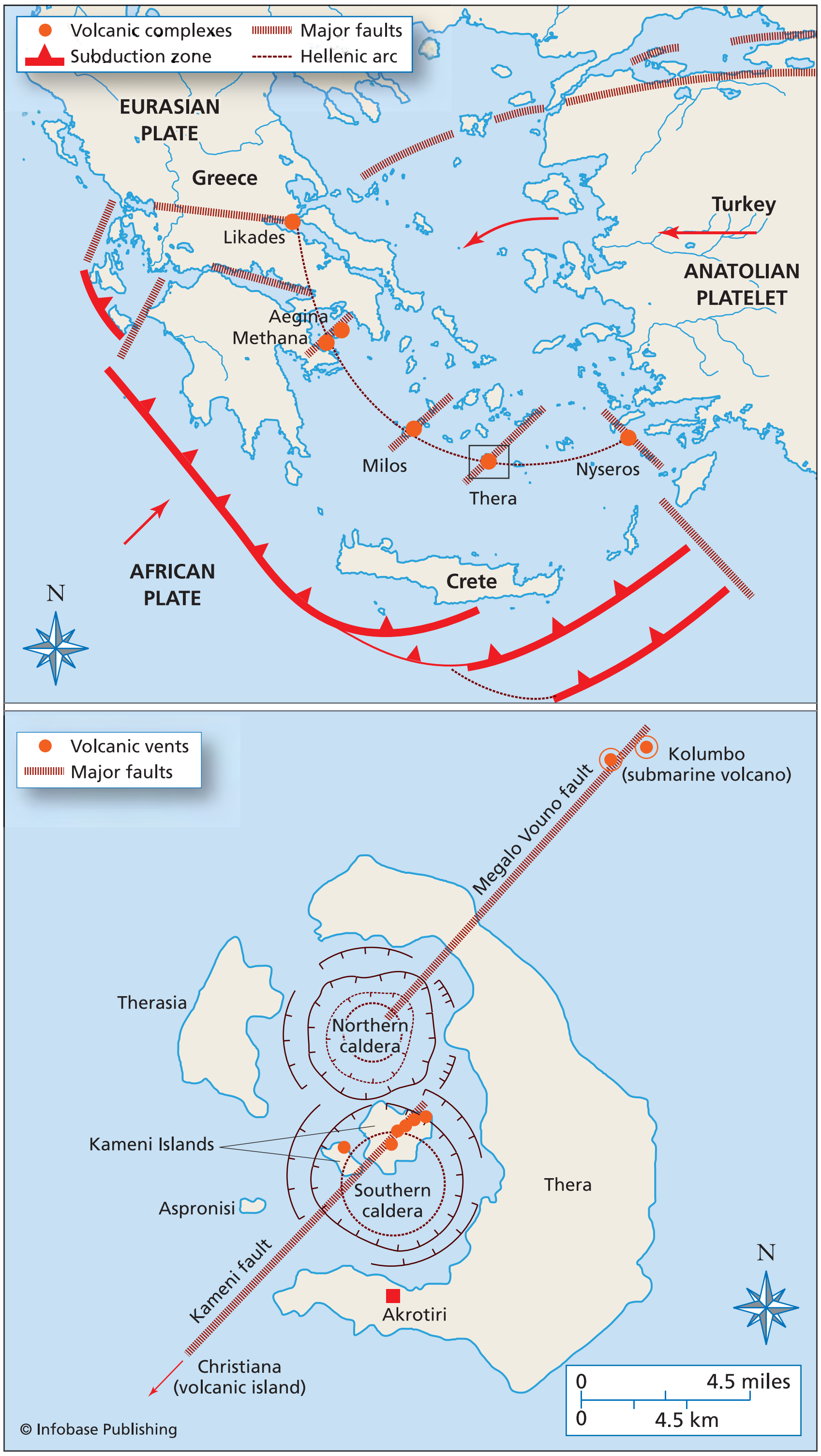
DESCRIPTIONS OF MAJOR ERUPTIONS FROM ISLAND AND CONTINENTAL-MARGIN ARC VOLCANOES

Volcanic arcs are important as the birthplace of continental crust, and they have also played a large role in the history of the world. Examination of some of the world's most significant volcanic eruptions helps understand the significance of arcs in natural and human history.

Thera, Greece, 3,650 Years before Present

One of the greatest volcanic eruptions in recorded history occurred approximately 3,650 years ago in the eastern Mediterranean region, then the cradle of civilization. Santorini is a small, elliptically shaped archipelago of islands, approximately 10 miles (16 km) across, located about 70 miles (110 km) north of the island of Crete. The islands are dark and ominous in stark contrast to the white limestone of the Greek islands, and they form ragged, 1,300-foot (390-m) peaks that seem to point up toward something that should be in the center of the ring-shaped archipelago but is no longer there. The peaks are pointing inward toward the center of a giant caldera complex that erupted in the late Bronze Age, approximately 3,650 years ago, devastating much of the eastern Mediterranean. The largest island on the rim of the caldera is Thera, and across two circular 900–1,000-foot (275–300-m) deep calderas rests the opposing island of Therasia, once part of the same volcano. In the center of the composite caldera complex are several smaller islands known as the Kameni Islands, which represent newer volcanic cones growing out of the old caldera.

Santorini and Thera (present-day Thíra) are part of the Cyclades islands that form part of the Hellenic island/continental-margin volcanic arc that stretches from western Turkey through Greece, lying above a subduction zone in the Mediterranean along which part of the African plate is being pushed beneath Europe and Asia. Volcanoes in the Hellenic arc are widely spaced, and numerous earthquakes also characterize the region. The area was apparently densely populated before the massive eruption 3,650 years ago, as remnants of Bronze Age and earlier Neolithic settlements and villages along the coastal Aegean are buried in ash from Thera. Settlers that arrived about 6,000–7,000 years ago and traded with Crete and Greece populated the island of Thera. In 1967 archaeologists discovered a Bronze Age city buried by ash from the eruption, and uncovered numerous paved streets and frescos, indicating that the city was at least the size of Pompeii, Italy, when it was buried by the eruption of Vesuvius more than 1,700 years later. At the time of the eruption the region was dominated by the Minoan culture, derived from Crete. The eruption occurred while a primitive form of writing was used by the Minoans, but has not been deciphered, and the Greek language had not yet been codified in writing. Thus no local texts record the eruption, although Hebrew text was in use in nearby Egypt and Israel. Some scholars have tried to link the eruption of Thera with biblical events such as the plagues, days of darkness, and parting of the Red Sea during the exodus of the Israelites from Egypt, although the timing of the eruption seems to be off by a couple of centuries for such a correlation to be made. The best current estimates for the age of the eruption are between 1690 and 1620 B.C.E.



Map of the eastern Mediterranean (top) showing the tectonic setting of Thera in the Hellenic volcanic arc. Note that Thera is located along a major fault above a subduction zone. Detailed map (bottom) of Santorini archipelago, showing modern Thera and the large calderas that collapsed 3,650 years ago.

Before the cataclysmic eruption, the Santorini islands existed as one giant volcano known to the Greeks as Stronghyle (Strongulè), or the round one, now referred to as Thíra. There are no known written firsthand accounts of the eruption of Thera, so the eruption history has been established by geological mapping and examination of the historical and archaeological records of devastation across the Mediterranean region. Volcanism on the island seems to have started 1 to 2 million years ago, and continues to this day. Large eruptions are known from 100,000 and 80,000 years ago, as well as 54,000, 37,000, and 16,000 years ago, then finally 3,500 years ago. The inside of Thera's caldera is marked by striking layers of black lava alternating with red and white ash layers, capped by a 200-foot (60-m) thick layer of pink to white ash and pumice that represents the deposits from the cataclysmic Bronze Age eruption. Ash from the eruption spread over the entire eastern Mediterranean and also fell on North Africa and across much of the Middle East. The most violent eruptions are thought to have occurred when the calderas collapsed and sea water rushed into the crater, forming a tremendous steam eruption and tsunami. The tsunami moved quickly across the Mediterranean, devastating coastal communities in Crete, Greece, Turkey, North Africa, and Israel. The tsunami was so powerful that it caused the Nile to run upstream for hundreds of miles (several hundred km).

Detailed reconstructions of the eruption sequence reveal four main phases. The first was a massive eruption of ash and pumice ejected high into the atmosphere, collapsing back on Thera and covering nearby oceans with 20 feet of pyroclastic deposits. This phase was probably a Plinian eruption column, and its devastating effects on Thera made the island uninhabitable. Approximately 20 years passed before activity continued, and some settlers tried to reinhabit the island. Huge fissures in the volcano began to open during the second phase, and seawater entered these, initiating large steam eruptions and mudflows and leaving deposits up to 65 feet (20 m) thick. The third phase was the most cataclysmic and followed quickly after the second phase, as seawater began to enter deep into the magma chamber, initiating huge blasts that were heard across southern Europe, northern Africa, and the Middle East. Sonic blasts and pressure waves would have been felt for thousands of miles around. Huge amounts of ash and aerosols were ejected into the atmosphere, probably causing several days of virtual darkness over the eastern Mediterranean. The fourth phase of the eruption was marked by continued production of pyroclastic flows, settling many layers of ash, pumice, and other pyroclastic deposits around the island and nearby Aegean. Most estimates of the amount of material ejected during the eruption fall around 20 cubic miles (80 km^3), although some estimates are twice that amount. Ash layers from the eruption of Thera have been found in Egypt, Turkey, other Greek islands, and the Middle East.

Thera undoubtedly caused global atmospheric changes after ejecting so much material into the upper atmosphere. Data from Greenland ice cores indicate that a major volcanic eruption lowered Northern Hemisphere temperatures by ejecting aerosols and sulfuric acid droplets into the atmosphere in 1645 B.C.E. Additional evidence of an atmospheric cooling event caused by the eruption of Thera comes from tree-ring data from ancient bristle-cone pines in California, some of the oldest living plants on Earth. These trees, and other buried tree limbs from Ireland, indicate a pronounced cooling period from 1630 to 20 B.C.E. European and Turkish tree-ring data have shown cooling between 1637 and 28 B.C.E. Chinese records show that at this time there were unusual acidic fogs (probably sulfuric acid) and cold summers, followed by a period of drought and famine. The eruption of Thera therefore not only destroyed the Minoan civilization, but also changed atmospheric conditions globally, forming frosts in California and killing tea crops in China.

The eruption of Thera seems to coincide with the fall of Minoan civilization, certainly in the Santorini archipelago, and also on Crete and throughout the eastern Mediterranean. The cause of the collapse of Minoan society was probably multifold, including earthquakes that preceded the eruption, ash falls, and 30-foot (9-m) high tsunamis that swept the eastern Mediterranean from the eruption. Since the Minoans were sea merchants, tsunamis would have devastated their fleet, harbor facilities, and coastal towns, causing such widespread destruction that the entire structure of the society fell apart. Even vessels at sea would have been battered by the atmospheric pressure waves, covered in ash and pumice, and stranded in floating pumice far from coastal ports. Crops were covered with ash, and palaces and homes were destroyed by earthquakes. The ash was acidic, so crops would have been ruined for years, leading to widespread famine and disease, driving people to seek relief by leaving Crete and the homeland of the Minoan culture. Many of the survivors are thought to have migrated to Greece and North Africa, including the Nile delta region, Tunisia, and to Levant, where the fleeing Minoans became known as Philistines.

Vesuvius, 79 C.E.

The most famous volcanic eruption of all time is probably that of Vesuvius in the year 79 C.E. Mount Vesuvius is the only active volcano on the European mainland, towering 4,195 feet (1,279 m) above the densely populated areas of Naples, Herculaneum, and surrounding communities in southern Italy. Vesuvius is an arc volcano related to the subduction of oceanic crust to the east of Italy beneath the Italian peninsula, and the volcano rises from the plain of Campania between the Apennine Mountains to the east and the Tyrrhenian Sea to the west. The volcano developed inside the collapsed caldera of an older volcano known as Monte Somma, only a small part of which remains along the northern rim of Vesuvius. Monte Somma and Vesuvius have had at least five major eruptions in the past 4,000 years, including 1550 and 217 B.C.E., and 79, 472, and 1631 C.E. There have been at least 50 minor eruptions of Vesuvius since 79 C.E.

Ash from the 79 C.E. eruption buried the towns of Pompeii, Herculaneum, and Stabiae in present-day Italy and killed tens of thousands of people. Before the eruption Pompeii was a well-known center of commerce, home to approximately 20,000. The area was known especially for its wines, cabbage, and fish sauce, and was also a popular resort area for wealthy Roman citizens. Pompeii became wealthy and homes were elaborately decorated with statues, patterned tile floors, and frescoes. The city built a forum, several theaters, and a huge amphitheater in which 20,000 spectators could watch gladiators fight each other or animals, with the loser usually being killed.

A large caldera north of Vesuvius presently has molten magma moving beneath the surface, causing a variety of volcanic phenomena that have inspired many legends. The Phlegraean Fields is the name given to a region where there are many steaming fumaroles spewing sulfurous gases and boiling mudpots, which may have inspired the Roman poet Virgil's description of the entrance to the underworld. The land surface in the caldera rises and falls with the movement of magma below the surface. This is most evident near the sea, where shorelines have moved up and down relative to coastal structures. At Pozzuoli the ancient Temple of Serapis lies partly submerged near the coast. The marble pillars of the temple show evidence of having been previously submerged, as they are partly bored through by marine organisms, leaving visible holes in the pillars. Charles Lyell, in his famous treatise *Principles of Geology,* used this observation to demonstrate that land can subside and be uplifted relative to sea level. A few miles north of Pozzuoli the ancient town of Port Julius is completely submerged beneath the sea, showing that subsidence has been ongoing for thousands of years.

Before the cataclysmic eruption in 79, the Campanians of southern Italy had forgotten that Vesuvius was a volcano and did not perceive any threat from the mountain, even though 50 years earlier the geographer Strabo had described many volcanic features of the mountain. The crater lake at the top of the mountain was used by the rebelling gladiator Sparticus and his cohorts to hide from the Roman army in 72 C.E., neither side of whom was aware of the danger of the crater. There were other signs that the volcano was returning to life. In 62 C.E. a powerful earthquake shook the region, damaging many structures and causing the water reservoir for Pompeii to collapse, flooding the town and killing and injuring many. It is likely that poisonous volcanic gases also escaped through newly opened fractures at this time, as Roman historians and philosophers write of a flock of hundreds of sheep dying mysteriously near Pompeii by a pestilence from within the Earth. The descriptions are reminiscent of the poison carbon dioxide gases emitted from some volcanoes, such as the disasters of Lake Nyos in Cameroon in 1984 and 1986. More earthquakes followed, including one in 63 C.E. that violently shook the theater while the emperor Nero was singing to a captive audience. Instead of evacuating the theater, it was said that Nero was convinced his voice was ever stronger and perhaps excited the gods of the underworld.

On August 24, 79 C.E., Vesuvius erupted after several years of earthquakes. The initial blast launched two and a half cubic miles (10 km^3) of pumice, ash, and other volcanic material into the air, forming a mushroom cloud that expanded in the stratosphere. This first phase of the eruption lasted 12 hours, during which time Pompeii's terrified residents were pelted with blocks of pumice and a rain of volcanic ash that was falling on the city at a rate of 7–8 inches (15–20 cm) per hour. People were hiding in buildings and fleeing through the artificially darkened streets, many collapsing and dying from asphyxiation. Soon the weight of the ash caused roofs to collapse on structures throughout the city, killing thousands. The ash quickly buried Pompeii under 10 feet (3 m) of volcanic debris. About half a day after the eruption began, the eruption column began to collapse from decreasing pressure from the magma chamber, and the eruption entered a new phase. At this stage pyroclastic flows known as nuées ardentes began flowing down the sides of the volcano. These flows consisted of a mixture of hot gases, volcanic ash, pumice, and other particles; they raced downhill at hundreds of miles (km) per hour while maintaining temperatures of 1,800°F (1,000°C) or more. These hot pyroclastic flows ripped up and ignited anything in their path, and Herculaneum was first in that path.

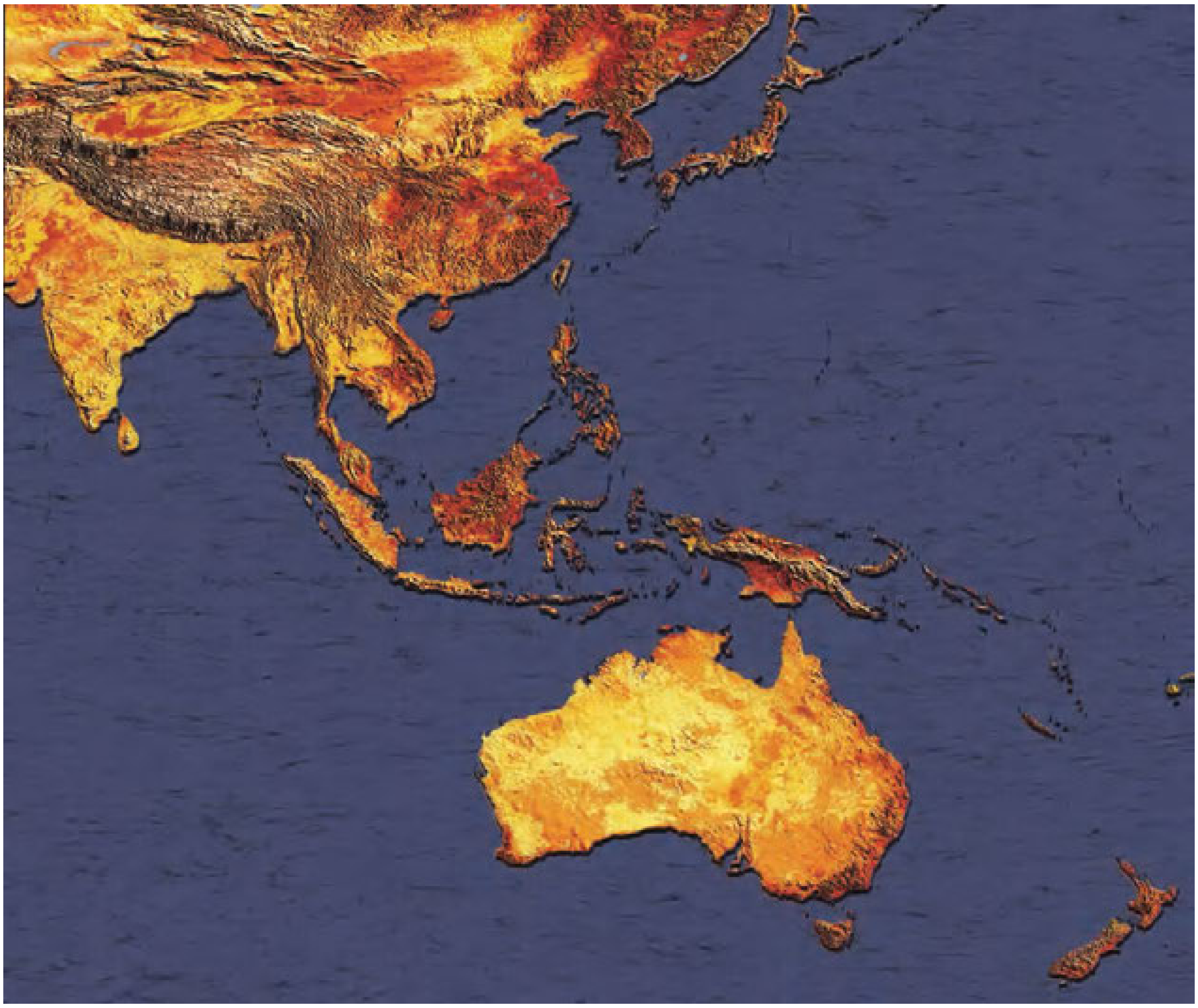
Successive pyroclastic flows together killed about 4,000 people in Herculaneum and Pompeii, and neighboring towns suffered similar fates after the initial blast. During the second phase of the massive eruption huge quantities of ash were blown up to 20 miles (32 km) into the atmosphere, alternately surging upward and dropping tons of ash onto the surrounding region and killing most of the people who were not killed in the initial eruption. Daylight was quickly turned into a dark, impenetrable night, and the town of Pompeii was buried under another 6 to 7 feet (~2 m) of ash. Thick ash also accumulated on the slopes of the volcano and was quickly saturated with water from rains created by the volcanic eruption. Water-saturated mudflows called lahars moved swiftly down the slopes of Vesuvius, burying the town of Herculaneum under additional volcanic layers up to 65 feet (20 m) thick, and covering Pompeii by up to 20 feet (5 m) of mud. The towns of Herculaneum and Pompeii were not uncovered until archaeologists discovered their ruins nearly 2,000 years later when, in 1699 the Italian scientist Giuseppe Marcrini dug into an elevated mound and discovered parts of the buried city of Pompeii. The public was not interested in the early 1700s, however, and the region's history remained obscure. For the next century wealthy landowners discovered that if they dug tunnels through the solidified ash, they could fund ancient statues, bronze pieces, and other valuables that they used to decorate their homes. It was not until Italy became unified in 1860 and the archaeologist Giuseppe Fiorelli was put in charge of excavations in southern Italy that looting changed to systematic excavation and study.

This area has since been rebuilt, with farmland covering much of Pompeii, and the town of Ercolano now lies on top of the 20 feet (6 m) of ash that buried Herculaneum. Archaeological investigation at both sites, however, has led to a wealth of information about life in ancient Italy, and Pompeii in particular has proven to be a valuable time capsule preserved in pristine condition by the encapsulating volcanic ash that entrapped so many people in their homes or trying to escape into the streets or elsewhere. Vesuvius is still active, and has experienced many eruptions since the famous eruption in 79 C.E.

The 72 C.E. eruption of Vesuvius is the source of some terms commonly used to describe features of volcanic eruptions. Pliny the Elder, the Roman naturalist and naval officer in charge of a squadron of vessels in the Bay of Naples during the eruption, commanded one of his vessels to move toward the mountain during the initial eruption for a better view and to rescue a friend. Both efforts failed, as the eruption was too intense to approach, so he sailed to Stabiae to the south to attempt to save another friend. Pliny the Elder died there, apparently from a heart attack brought on by struggling through the thick ash in the city. In an account of the death of his uncle and of the eruption given to the Roman historian Tacitus, Pliny the Younger (the Elder's nephew) described the mushroom cloud associated with the initial eruption as being like an umbrella where the lower column rose up in a thin pipe then expanded outward in all directions at the top. The common term *Plinian eruption column* is taken from these descriptions.

Tambora, Indonesia, 1815

The largest volcanic eruption ever recorded is that of the Indonesian island arc volcano Tambora in 1815. This eruption initially killed an estimated 92,000 people and sent so much particulate matter into the atmosphere that it influenced the climate of the planet, cooling the surface and changing patterns of rainfall globally. The year after the eruption is known as "the year without a summer" in reference to the global cooling caused by the eruption, although people at the time did not know the reason for the cooling. In cooler climates the "year without



Colored satellite image of Indonesia and Philippines. The Indonesian region is the site of many subduction zones and island arc systems and has experienced some of the most dramatic and catastrophic volcanic eruptions in history. *(Dynamic Earth Imaging/Photo Researchers, Inc.)*

a summer" saw snow throughout the summer and crops could not grow. Great masses of U.S. farmers moved from New England to the Midwest and Central Plains seeking a better climate for growing crops. This mass migration and population of the American Midwest was all because of a volcanic eruption on the other side of the world.

Tambora is located in the Indonesian region, a chain of thousands of islands that stretch from Southeast Asia to Australia. The tectonic origins of these islands are complex and varied, but many of the islands along the southwest part of the chain are volcanic, formed above the Sumatra-Sunda trench system. Fertile soils host tropical rain forests, many of which have been deforested and replaced by tobacco, tea, coffee and spice plantations (hence their nickname, "spice islands"). This trench marks the edge of subduction of the Australian plate beneath the Philippine-Eurasian plates, and formed a chain of convergent-margin island arc volcanoes above the subduction zone. Tambora is one of these volcanoes, located on the island of Sumbawa, east of Java. Tambora is unique among the volcanoes of the Indonesian chain as it is located farther from the trench (210 miles; 340 km) and farther above the subduction zone (110 miles; 175 km) than other volcanoes in the chain. This is related to the fact that Tambora is located at the junction of subducting continental crust from the Australian plate and subducting oceanic crust from the Indian plate. A major fault cutting across the convergent boundary is related to this transition, and the magmas that feed Tambora seem to have risen through fractures along this fault.

Tambora has a history of volcanic eruptions extending back at least 50,000 years. The age difference between successive volcanic layers is large, and there appears to have been as many as 5,000 years between individual large eruptions. This is a large time interval for most volcanoes and may be related to Tambora's unusual tectonic setting far from the trench along a fault zone related to differences between the types of material being subducted on either side of the fault.

In 1812 Tambora started reawakening with a series of earthquakes plus small steam and ash eruptions. Inhabitants of the region did not pay much attention to these warnings, having not remembered the ancient eruptions of 5,000 years past. On April 5, 1815, Tambora erupted with an explosion heard 800 miles (1,300 km) away in Jakarta. Ash probably reached more than 15 miles (25 km) into the atmosphere, and this was only the beginning of what was to be one of history's greatest eruptions. Five days after the initial blast a series of huge explosions rocked the island, sending ash and pumice 25 miles (40 km) into the atmosphere, and sending hot pyroclastic flows (nuées ardentes) tumbling down the flanks of the volcano and into the sea. When the hot flows entered the cold water, steam eruptions sent additional material into the atmosphere, creating a scene of massive explosive volcanism and wreaking havoc on the surrounding land and marine ecosystems. More than 36 cubic miles (150 km^3) of material were erupted during these explosions from Tambora, more than 100 times the volume of the Mount St. Helens eruption in Washington State of 1980.

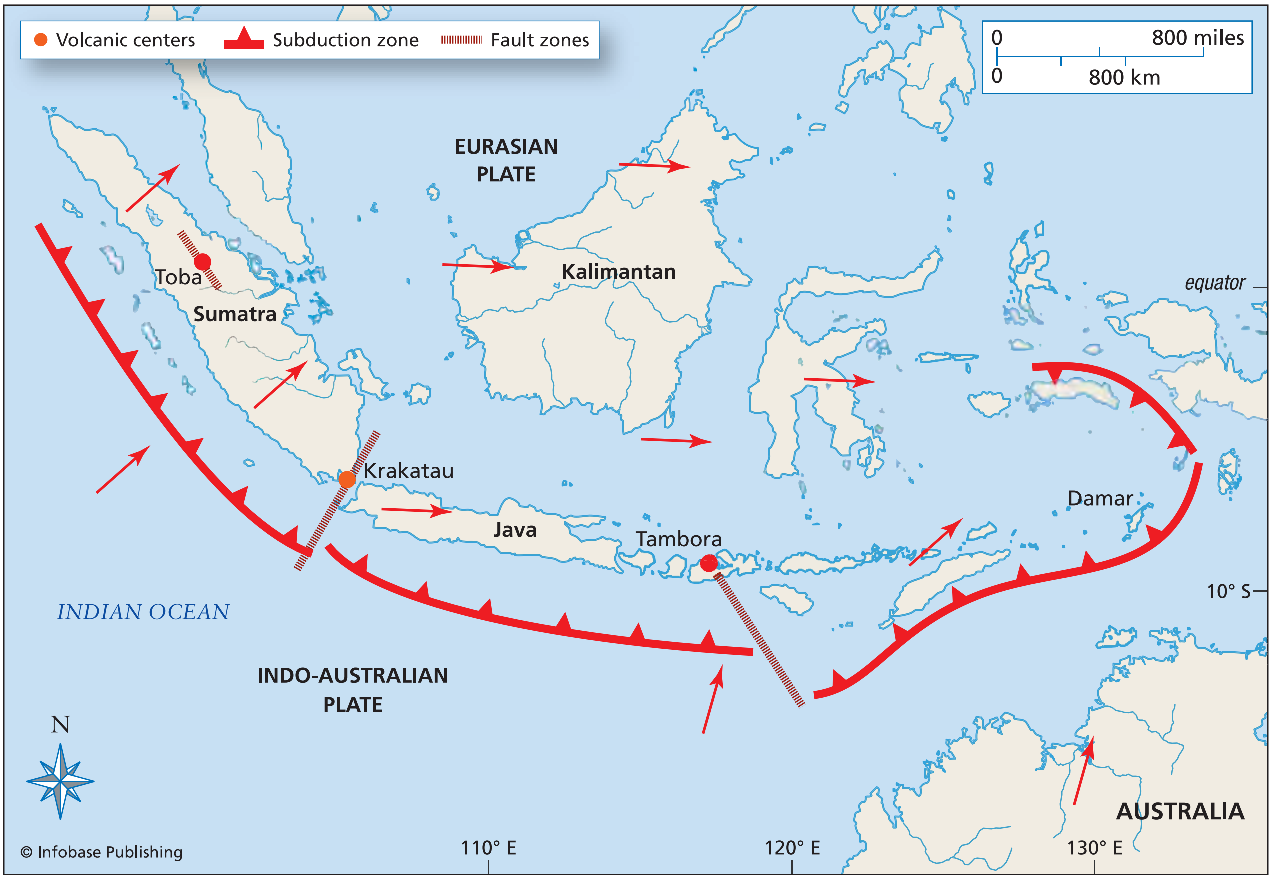
Ash and other volcanic particles such as pumice from the April eruptions of Tambora covered huge areas that stretched many hundreds of miles across Indonesia. Towns located within a few tens of miles experienced strong, hurricane-force winds that carried rock fragments and ash, burying much in their path and causing widespread death and destruction. The ash caused a nightlike darkness that lasted for days even in locations 40 miles (65 km) from the eruption center, so dense was the ash. Roofs collapsed from the weight of the ash, and 15-foot (4.5-m) tall tsunamis were formed when the pyroclastic flows entered the sea. These tsunamis swept far inland in low-lying areas, killing and sweeping away many people and livestock. A solid layer of ash, lumber, and bodies formed on the sea extending several miles west from the island of Sumbawa, and pieces of this floating mass drifted off across the Java Sea. Although it is difficult to estimate, at least 92,000 people were killed in this eruption. Crops were incinerated or poisoned, and irrigation systems destroyed, causing additional famine and disease after the eruption ceased, killing tens of thousands of people who had survived the initial eruption, and forcing hundreds of thousands to migrate to neighboring islands.

The atmospheric effects of the eruption of Tambora were profound. During the eruptions Tambora shot huge amounts of sulfur dioxide and steam into the atmosphere and contaminated surface and groundwater systems. Much of the sulfur dioxide rained onto nearby lands and islands, causing illness including persistent diarrhea. Huge amounts of gas also entered the upper atmosphere, causing changes in weather patterns throughout the world. In the upper atmosphere sulfur dioxide combines with water molecules to form persistent sulfuric acid aerosols, which reflect large amounts of sunlight to space and cause a global cooling effect. Weather data show that the Northern Hemisphere experienced temperatures as many as 10 degrees Celsius cooler than normal for three years following the eruption, and much of that cooling is attributed to the aerosols in the upper atmosphere. The Indian Ocean monsoon was disrupted to such an extent that some regions expecting rain were plagued with drought instead, then when the rains were supposed to end, they finally came—but too late for the crops. Widespread famine, then an epidemic of cholera, engulfed north India and surrounding areas (present-day Pakistan and Bangladesh). In eastern China the Yangtze and Yellow Rivers experienced severe floods, destroying crops and killing many people. The cholera plague that started in India soon spread to Egypt, killing 12 percent of the population, then to Europe, where hundreds of thousands perished. The global outbreak soon spread to North America, hitting the immigrant cities of New York and Montreal with particular severity, where hundreds of people died each day. The cholera plague, lasting from 1817 through 1823, is one of the long-term secondary hazards of volcanic eruptions. The uncountable deaths from the secondary effects of the eruption thus far outnumber the deaths from the initial eruption.

The year 1816 is known as the "year without a summer," because of the atmospheric cooling from the sulfur dioxide released from Tambora. Snow fell in many areas across Europe and in some places was colored yellow and red from the volcanic particles in the atmosphere. Crops failed, people suffered, and social and economic unrest resulted from the poor weather. Then the Napoleonic Wars soon erupted. Famine swept Europe, hitting France especially hard, with food and antitax riots breaking out in many places. The number of deaths from the famine in Europe is estimated at another 100,000.

North America also suffered from the global cooling from Tambora. The New England states were hardest hit, experiencing a cold drought, with deep frosts and snow storms even in the typically summer months of June, July, and August. Crops failed, livestock had nothing to eat and perished, and many farmers resorted to fishing in streams to get food for their animals. Others were unable to cope with loss of crops and rising food prices, and many became poor and dependent on charity. Others migrated to the fertile warmer plains of the American Midwest, expanding the country's wheat belt westward.

The eruption of Tambora illustrates the difficulty in estimating the numbers of deaths and the actual cost to the global population of a volcanic eruption. It is hard enough to determine the deaths in remote areas that have been affected by a catastrophe of this magnitude, but when secondary effects such as dis-



Map of Indonesia showing the locations of Tambora and Krakatau, both along faults above a subduction zone ease, global epidemics, loss of crops, and changes of climate are taken into account, the numbers of those affected climbs by hundreds of thousands, millions, or more.

Krakatau, Indonesia, 1883

Indonesia has seen other catastrophic volcanic eruptions in addition to Tambora. The island nation of Indonesia has more volcanoes than any other country in the world, with more than 130 known active volcanoes in this island-continental margin-arc system. These volcanoes have been responsible for about one-third of all the deaths attributed to volcanic eruptions in the world. Indonesia stretches for more than 3,000 miles (5,000 km) between Southeast Asia and Australia and is characterized by fertile soils and warm climates. It is one of the most densely populated places on Earth. Its main islands include, from Northwest to Southeast, Sumatra, Java, Kalimantan (formerly Borneo), Sulawesi (formerly Celebes), and the Sunda Islands. The country averages one volcanic eruption per month; because of the dense population, Indonesia suffers from approximately one-third of the world's fatalities from volcanic eruptions.

One of the most spectacular and devastating eruptions of all time was that of 1883 from Krakatau, an uninhabited island in the Sunda Strait off the coast of the islands of Java and Sumatra. This eruption generated a sonic blast heard thousands of miles away, spewed enormous quantities of ash into the atmosphere, and initiated a huge tsunami that killed roughly 40,000 people and wiped out more than 160 towns. The main eruption lasted for three days, and the huge amounts of ash ejected into the atmosphere circled the globe, remained in the atmosphere for more than three years, forming spectacular sunsets and affecting global climate. Locally the ash covered nearby islands, killing crops, natural jungle vegetation, and wildlife, but most natural species returned within a few years.

Like Tambora, Krakatau is located at an anomalous location in the Indonesian arc. To the southeast of Krakatau, the volcanoes on the island of Java are aligned in an east-west direction, lying above the subducting Indo-Australian plate. To the northwest of Krakatau volcanoes on Sumatra are aligned in a northwest-southeast direction. Krakatau is thus located at a major bend in the Indonesian arc and lies along with a few other smaller volcanoes above the Krakatau fault zone that strikes through the Sunda Strait. This fault zone is accommodating differential motion between Java and Sumatra. Java is moving east at 1.5 inches (4 cm per year), whereas Sumatra is moving northeast at 1.5 inches (4 cm per year) and rotating in a clockwise sense, resulting in a zone of oblique extension along the Krakatau fault zone in the Sunda Strait. The faults and fractures formed from this differential motion between the islands provide easy pathways for the magma and other fluids to migrate from great depths above the subduction zone to the surface. So like Tambora, Krakatau has had unusually large volcanic eruptions and is located at an anomalous structural setting in the Indonesian arc.

Legends in the Indonesian islands speak of several huge eruptions from the Sunda Strait area, and geological investigations confirm many deposits and calderas from ancient events. Before the 1883 eruption Krakatau consisted of several different islands including Perbuwatan in the north, and Danan and Rakata in the south. The 1883 eruption emptied a large underground magma chamber and formed a large caldera complex. During the 1883 eruption Perbuwatan, Danan, and half of Rakata collapsed into the caldera and sank below sea level. Since then a resurgent dome has grown out of the caldera, emerging above sea level as a new island in 1927. The new island, named Anak Krakatau (child of Krakatau), is growing to repeat the cycle of cataclysmic eruptions in the Sunda Strait.

Before the 1883 eruption the Sunda Strait was densely populated with many small villages built from bamboo with palm-thatched roofs, and other local materials. Krakatau is located in the middle of the strait, with many arms of the strait extending radially away into the islands of Sumatra and Java. Many villages, such as Telok Betong, lay at the ends of these progressively narrowing bays, pointed directly at Krakatau. These villages were popular with trading ships from the Indian Ocean which stopped to obtain supplies before heading through the Sunda Strait to the East Indies. The group of islands centered on Krakatau in the middle of the strait was a familiar landmark for these sailors.

Although not widely appreciated as such at the time, the first signs that Krakatau was not a dormant volcano but was about to become very active appeared in 1860 and 1861 with small eruptions, then a series of earthquakes between 1877 and 1880. On May 20, 1883, Krakatau entered a violent eruption phase, witnessed by ships sailing through the Sunda Strait. The initial eruption sent a seven-mile (11-km) high plume above the strait, with the eruption heard 100 miles (160 km) away in Jakarta. As the eruption expanded, ash covered villages in a 40-mile (60-km) radius. For several months the volcano continued to erupt sporadically, covering the straits and surrounding villages with ash and pumice, while the earthquakes continued.

On August 26, the form of the eruptions took a severe turn for the worse. A series of extremely explosive eruptions sent an ash column 15 miles (25 km) into the atmosphere, sending many pyroclastic flows and nuées ardentes spilling down the island slopes and into the sea. Tsunamis associated with the flows and earthquakes sent waves into the coastal areas surrounding the Sunda Strait, destroying or damaging many villages on Sumatra and Java. Ships passing through the straits were covered with ash, while others were washed ashore and shipwrecked by the many and increasingly large tsunamis.

On August 27, Krakatau put on its final show, exploding with a massive eruption that pulverized the island and sent an eruption column 25 miles (40 km) into the atmosphere. The blasts from the eruption were heard as far away as Australia, the Philippines, and Sri Lanka. Atmospheric pressure waves broke windows on surrounding islands and traveled around the world as many as seven times, reaching the antipode (area on the exactly opposite side of the Earth from the eruption) at Bogatá, Colombia, 19 hours after the eruption. The amount of lava and debris erupted is estimated at 18–20 cubic miles (75–80 km^3), making this one of the largest eruptions known in the past several centuries. Many sections of the volcano collapsed into the sea, forming steep-walled escarpments cutting through the volcanic core, some of which are preserved to this day. These massive landslides were related to the collapse of the caldera beneath Krakatau and contributed to huge tsunamis that ravaged the shores of the Sunda Strait, with average heights of 50 feet (15 m), but reaching up to 140 feet (40 m) where the V-shaped bays amplified wave height. Many of the small villages were swept away with no trace, boats were swept miles inland or ripped from their moorings, and thousands of residents perished in isolated villages in the Sunda Strait.

Although it is uncertain how many people died in the volcanic eruption and associated tsunamis, the Dutch colonial government estimated in 1883 that 36,417 people died, with most of these deaths (perhaps 90 percent) from the tsunami. Several thousand people were also killed by extremely powerful nuées ardentes, or glowing clouds of hot ash that raced across the Sunda Strait on cushions of hot air and steam. These clouds burned and suffocated all who were unfortunate enough to be in their direct paths.

Tsunamis from the eruption spread out across the Indian Ocean and caused destruction along much of the coastal regions of the entire Indian Ocean, eventually moving around the world. Although documentation of this Indonesian tsunami is not nearly as good as that from the 2004 tsunami, many reports of the tsunami generated from Krakatau document this event. Residents of coastal India reported the sea suddenly receding to unprecedented levels, stranding fish that were quickly picked up by residents, many of whom were then washed away by large waves. The waves spread into the Atlantic Ocean and were detected in France, and a seven-foot (2-m) high tsunami beached fishing vessels in Auckland, New Zealand.

Weeks after the eruption huge floating piles of debris and bodies were still floating in the Sunda Strait, Java Strait, and Indian Ocean, providing grim reminders of the disaster to sailors in the area. Some areas were so densely packed with debris that sailors reported those regions looked like solid ground, and one could walk across the surface. Fields of pumice from Krakatau reportedly washed up on the shores of Africa a year after the eruption, some mixed with human skeletal remains. Other pumice rafts carried live plant seeds and species to distant shores, introducing exotic species across oceans that normally acted as barriers to plant migration.

Ash from the eruption fell more than 1,500 miles (2,500 km) from the eruption for days after it, and many fine particles remained in the atmosphere for years, spreading across the globe by atmospheric currents. The ash and sulfur dioxide from the eruption caused a lowering of global temperatures by several degrees and created spectacular sunsets and atmospheric light phenomena by reflected and refracted sunlight through the particles and gas emitted into the atmosphere.

On western Java, one of the most densely populated regions in the world, destruction on the Ujong Kulon Peninsula was so intense that it was designated a national park, as a reminder of the power and continued potential for destruction from Krakatau. Such designations of hazardous coastal regions and other areas of potential destruction as national parks and monuments is good practice for decreasing the severity of future natural eruptions and processes.

Krakatau began rebuilding new cinder cones that emerged from beneath the waves in 1927 through 1929, when the new island, Anak Krakatau (child of Krakatau), went into a rapid growth phase. Several cinder cones have now risen to heights approaching 600 feet (190 m) above sea level. The cinder cones will undoubtedly continue to grow until Krakatau's next catastrophic caldera collapse eruption.

Mount Pelée, Martinique, 1902

Martinique was a quiet, West Indian island first discovered by Europeans in the person of Christopher Columbus in 1502. The native Carib people were killed off or assimilated into the black slave population brought by the French colonizers to operate the sugar, tobacco, and coffee plantations, and they exported sugar beginning in the mid-1600s. The city of St. Pierre, on the northwest side of the island, became the main seaport, as well as the cultural, educational, and commercial center of Martinique. The city became known as the "Paris of the West Indies," with many rum distilleries, red-roofed white masonry buildings, banks, schools, beautiful beaches, all framed by a picturesque volcano in the background.

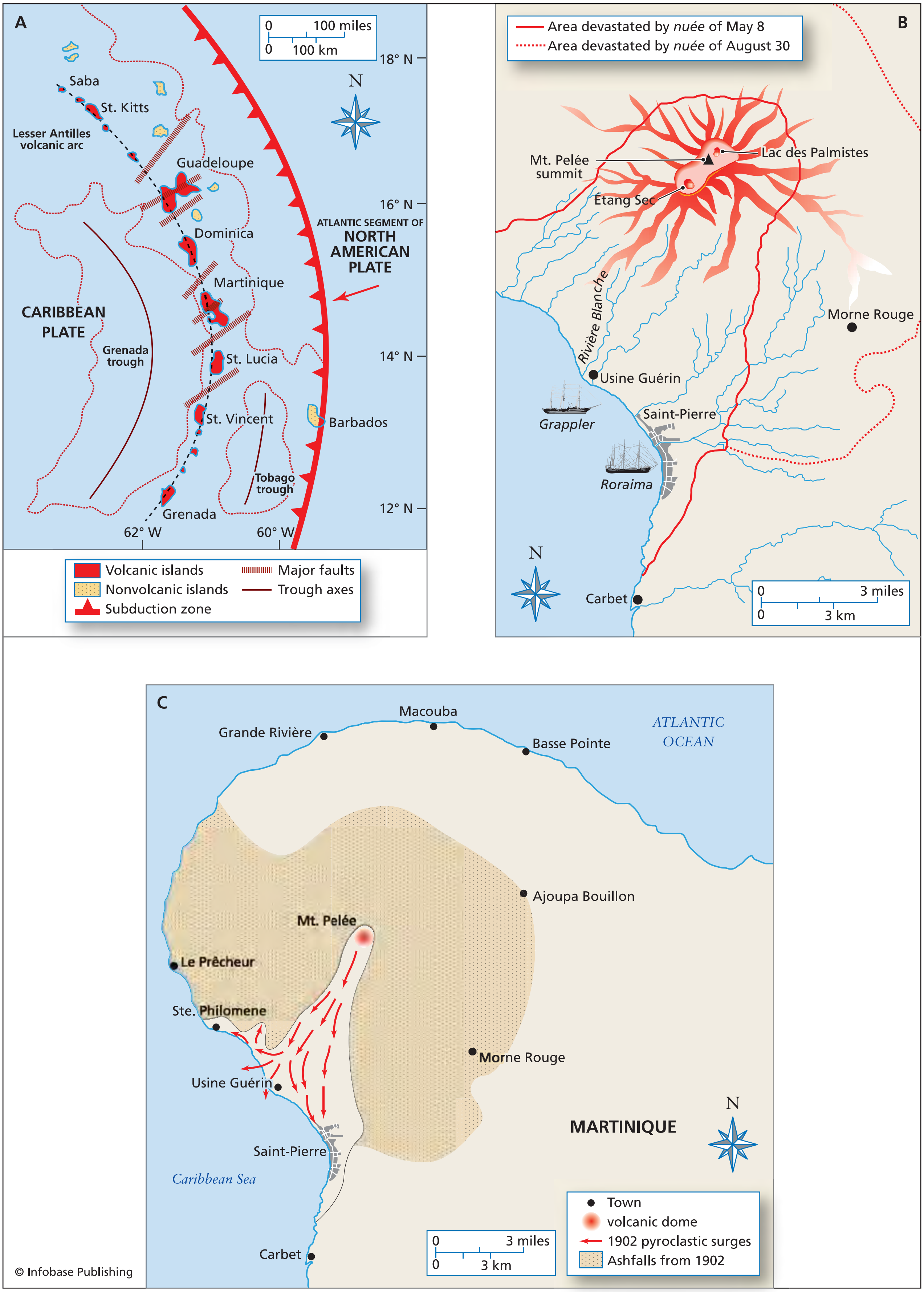
The island is part of the Lesser Antilles arc, sitting above a west-dipping subduction zone built on the eastern margin of the Caribbean plate. Oceanic crust of the Atlantic Ocean basin that is part of the North American plate is being pushed beneath the Caribbean plate at about an inch (2 cm) per year. The oldest volcanoes on Martinique, including Morne Jacob, the Pitons du Carbet, and Mount Conil, emerged from the sea about 3–4 million years ago. They were built on a submarine island arc that had been active for approximately the last 16 million years. Pelée is a much younger volcano, first known to have erupted about 200,000 years ago. It rises to a height of 4,580 feet (1,397 m) on the north end of the island and has had major historic eruptions in 65 B.C.E., 280, and 1300, and smaller eruptions about every 50–150 years. Mount Pelée is located uphill and only six miles (10 km) from St. Pierre. It derives its name from the French word for bald (or peeled), after the eruptions of 1792 and 1851 that removed all vegetation from the top of the volcano.

Mount Pelée began to awaken slowly in 1898, when sulfurous gases were noticed coming out of a crater on top of the mountain and in the river Blanche, which flows through a gorge on the southwest flank of the volcano. Minor eruptions of steam became abundant in 1901, and additional gaseous emissions were common as well. In spring 1902 Mount Pelée began to show increased activity, with boiling lakes and intermittent minor pyroclastic flows and eruptions, associated with minor earthquake activity. All these phenomena were connected with the rise of magma beneath the volcano and served as warnings about the upcoming eruption. A dome of magma began growing in one of the craters on top of the volcano, then a huge, 650-foot (200-m) wide tower of solidified magma known as "the spine" formed a plug that rose to 375 feet (115 m) before the catastrophic May 8 eruption.

By April most people were becoming worried about the increasingly intense activity, and they congregated in St. Pierre to catch boats to leave the island. St. Pierre was located only six miles (~10 km) from the volcano. Landslides in the upper river Blanche triggered a series of massive mudflows that rushed down the river, while others crashed down the valley when water in the crater lake in L'Etang Sec, the main volcanic vent on Pelée, broke through a crack in the crater rim and escaped down the flank of the volcano. These landslides and mudflows were probably triggered by minor seismic activity associated with magma rising upward beneath Pelée. On May 3 groundwater began rushing out of fissures that opened in the ground and carried soil, trees, and carcasses of dead animals down through St. Pierre and out to sea. Flooding was widespread and destroyed many farms and villages, such as Le Prêcheur, carrying the wreckage downstream.

On May 4 a fissure opened in the ground in the village of Ajoupa Bouillon northeast of Pelée and caused a huge steam and mud eruption that killed several people. Floods and mudflows continued to flow down other rivers, including those that passed through St. Pierre. Submarine landslides ruptured communication cables and carried them to depths of a half mile (0.7 km). A larger eruption occurred on May 5, killing 40 people in a pyroclastic flow that raced down the river Blanche. Residents desperately wanted to leave the island for safety, but elections were five days away, and Governor Louis Mouttet did not want the inhabitants to leave for fear he might lose the election. He ordered the military to halt the exodus from the island. Governor Mouttet was running as the head of the békés, an ultraconservative white supremacist party opposed by a new mixed-race socialist party that was becoming increasingly powerful. A successful election by the socialists would have changed the balance of power in Martinique and other French colonies, so was resisted by any means (likely including election fraud) by the ruling békés. By this stage precursors to the eruption included strange behavior by animals and insects. A plague of armies of ants, venomous centipedes, poisonous snakes including pit vipers, and mammals began migrating in mass down the flanks of the volcano and invaded villages, plantations, and St. Pierre to the horror of residents. These insects and animals attacked people in factories, plantations, and homes, injuring and killing many. Poisonous gases killed birds in flight, which dropped on towns like ominous warnings from the sky. Mudflows continued down the volcano flanks and now included boiling lahars, one of which tore down the river Blanche, killing

(opposite page) (A) Map of the Caribbean and the Lesser Antilles arc, showing the location of Martinique and Mt. Pelée along a fault above a subduction zone; (B) map of the area around St. Pierre on Martinique devastated by the 1902 eruption; (C) map of the pyroclastic flows from the 1902 eruptions, in relation to the dome of Mount Pelée, and cities and settlements including St. Pierre, Carbet, Le Prêcheur


A
0 100 miles
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18° N
N
Saba
St. Kitts
Lesser Antilles volcanic arc
Guadeloupe
16° N
Dominica
ATLANTIC SEGMENT OF NORTH AMERICAN PLATE
Martinique
CARIBBEAN PLATE
Grenada trough
St. Lucia
14° N
St. Vincent
Barbados
Tobago trough
12° N
Grenada
62° W
60° W
Volcanic islands
Nonvolcanic islands
Subduction zone
Major faults
Trough axes
B
Area devastated by *nuée* of May 8
Area devastated by *nuée* of August 30
Mt. Pelée summit
Lac des Palmistes
Étang Sec
Rivière Blanche
Morne Rouge
Usine Guérin
Grappler
Saint-Pierre
Roraima
N
Carbet
0 3 miles
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C
Macouba
Grande Rivière
Basse Pointe
ATLANTIC OCEAN
Ajoupa Bouillon
Mt. Pelée
Le Prêcheur
Ste. Philomene
Morne Rouge
Usine Guérin
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MARTINIQUE
N
Caribbean Sea
Carbet
0 3 miles
0 3 km
Town
volcanic dome
1902 pyroclastic surges
Ashfalls from 1902
© Infobase Publishing

many people in factories and homes in the boiling mixture of mud, ash, and water. Others in St. Pierre were dying rapidly of a contagious plague caused by drinking water contaminated by ash and sewage. Workers on the docks went on strike, and there was little chance for anybody to escape the condemned city.

On May 6, residents of the city, now in a state of turmoil, woke to a new layer of ash covering city streets and fields. This ash was not from Pelée but from another massive eruption that had occurred overnight 80 miles (130 km) to the south on the British colony island of St. Vincent, where the volcano La Soufrière, killed 1,650 residents of that island. The Soufrière eruption triggered submarine slides that broke all communication lines to and from Martinique, totally isolating that island from the rest of the world during the disaster that was about to occur. Ironically, communication lines to St. Vincent remained intact and surviving residents there could dispatch cables to England for help. Ships were dispatched but when they arrived they assumed all the ash and debris in the water was from St. Vincent, and help was not sent to St. Pierre until much later, when it was realized that two major eruptions had occurred from two different volcanoes.

On May 7 the volcano was thundering with loud explosions heard throughout the Lesser Antilles. Smoke, fires, and flashes of lightning made for a frightening spectacle, especially at night when the fires reflected off the low-lying clouds and ash. Volcanic bombs were being spewed from Pelée and landing on homes and fields on the outskirts of St. Pierre, starting many fires. On May 7 Governor Mouttet and his wife visited St. Pierre from the capital, Fort-de-France, to try to convince residents that it was safe to remain and to vote in the elections. However, at 7:50 A.M. on May 8 several huge sonic blasts rocked the island and a tall eruption column rose quickly from the top of the volcano. A few minutes later a huge nuée ardente or glowing avalanche erupted from Mount Pelée at 2,200°F (900°C), and moved over the six miles (~10 km) to St. Pierre at 115 miles (185 km) per hour (some estimates are as high as 310 miles [500 km] per hour), reaching the city 10 minutes after the eruption began. This began as a lateral blast or a collapse of the eruption column, aimed directly at St. Pierre below. As the pyroclastic flow rushed down the mountain, it expanded and scorched forests, sugarcane fields, and villages on the flanks of the volcano. The temperature of the flow cooled to an estimated 410°–780°F (200°–400°C) by the time it reached the sea, but this was enough to burn almost anything in its path. When the hot ash cloud reached St. Pierre, it demolished buildings and ignited flash fires throughout the city. Thousands of casks of rum stored in the city ignited and flowed as rivers of fire to the sea, burning at temperatures high enough to melt glass. The eruption cloud continued past the city and screamed over the harbor on a cushion of hot steam, overturning and burning many ships at anchor, sending them to the seafloor and killing most sailors on board.

Many accounts of the eruption say that all but two of the city's 30,000 residents were killed. Although about 30 residents survived the initial eruption, more than 27,000 were killed in the first massive eruption. Most died in a matter of minutes during passage of the ash cloud, but others died slowly from suffocation from ash or volcanic gas. One of the survivors was a prisoner, Auguste Ciparis, who had been jailed for fighting and was spending his jail term in a deep, dungeonlike cell that sheltered him from the hot ash cloud. Ciparis spent the rest of his life paraded around freak shows in the United States by the Barnum and Bailey circus to show his badly burned body as "The Prisoner of St. Pierre." About 2,000 people from surrounding towns were killed in later eruptions. Governor Mouttet and his wife were buried in the flow and were never seen again.

After the catastrophic eruption magma continued to rise through the volcano and formed a new dome that rose above the crater's rim by the end of the month, and the "spine" rose to a height of 1,000 feet (300 m). Another pyroclastic eruption followed the same path on May 20, burning anything that had escaped the first eruption. Small eruptions continued to cover the region with ash until activity subsided in July 1905.

The 1902 eruption of Pelée was the first clearly documented example of a nuée ardente, or hot glowing avalanche cloud. Successive eruptions of Mount Pelée in 1904 provided additional documentation of this kind of eruption and its dangers to all in its path. Even though the amount of magma released in these flows may be relatively small, the destructiveness of these hot, fast-moving flows is dramatic.

Nevada del Ruiz, Colombia, 1985

The most deadly volcanic-induced disaster of modern times occurred in a relatively minor volcanic eruption in the Andes Mountains of South America. The Nevada del Ruiz volcano in Colombia entered an active phase in November 1984 and began to show rhythmically repeating harmonic earthquake tremors on November 10, 1985. At 9:37 P.M. that night a large Plinian eruption sent an ash cloud several miles into the atmosphere, and this ash settled on the ice cap on top of the mountain. This ash together with volcanic steam quickly melted large amounts of the ice, which mixed with the ash and formed giant lahars (mudflows) that swept down the east side of the mountain into the village of Chinchina, killing 1,800. The eruption continued and melted more ice that mixed with more ash, and sent additional, larger lahars westward. Some of these lahars moved nearly 30 miles (50 km) at nearly 30 miles per hour (50 km/hr), and under a thunderous roar buried the town of Armero beneath 26 feet (8 m) of mud. Twenty-two thousand people died in Armero that night. Many could have been saved, since warnings were issued before the mudflow, but the warnings went unheeded.

Nevada del Ruiz had experienced a year of intermittent precursory activity that indicated an eruption might occur, and the volcano was being studied by a group of Colombian geologists at the time of the eruption. At 3:05 P.M. on November 13, 1985, ranchers north of the volcano heard a low rumbling and observed a plume of black ash rise from the volcano and fall on the town of Armero, 45 miles (72 km) away about two hours later. By 4:00 P.M., local civil defense officials warned that an eruption was in progress and recommended that towns including Armero, Honda, and others be ready for immediate evacuation. After several hours of meetings the Red Cross ordered the evacuation of Armero at 7:30 P.M. Residents did not, however, hear the orders, and did not understand the danger moving their way.

At 9:08 P.M. two large explosions marked the start of a larger eruption, associated with a series of pyroclastic flows and surges that moved down the north flank of the volcano. The volcanic deposits moved across the ice cap on the mountain, scouring, melting, and covering it in various places. This released large amounts of melt water mixed with debris that moved down the slopes, quickly forming giant lahars that scoured the channels of the Nereidas, Molinos, Guali, Azufrado, and Lagunillas Rivers and picking up huge amounts of debris including rocks, soil, and vegetation in the process.

At 9:30 P.M. a Plinian eruption column was visible, rising to nearly seven miles (11 km), and it hurled blocks and bombs of andesitic pumice up to a couple of miles from the crater, with ash falling up to 250 miles (400 km) away. At 10:30 P.M., lahars began sweeping through the village of Chinchina, and additional warnings were sent to Armero. Later, survivors reported that electricity was out sporadically and many residents may not have heard the warnings. At 11:30 P.M. giant lahars surged into Armero in successive waves moving at 22–30 miles per hour (35–50 km/hr), sweeping away homes, cars, people, and livestock, and embedding all in 26 feet (8 m) of mud. Many survived the initial inundation but were trapped half-buried in the mud and died later of exposure.

Scientists have learned many lessons from Nevada del Ruiz that could be useful for saving lives in the future. First, even minor volcanic eruptions can trigger catastrophic mudflows under the right conditions, and geologic hazard maps should be made in areas of volcanism to understand the hazards and help emergency planning in times of eruption. Local topographic variations can focus lahars, enhancing their lethality in some places and spreading them out in others. Armero was located at the end of a canyon that focused the worst parts of the flow in the heart of the village. Understanding past hazards can help foreseeing what may happen in the future. If geologists had helped plan the location of Armero, they would have noticed that the town location was on top of an older lahar deposit that swept down the mountain in 1845, also killing all inhabitants more than a century earlier. Apparently the geologic record shows a number of repeated mudflows destroying villages at the site of Armero. A final lesson from Armero is that warning systems need to be in place, and even simple alarm systems can save thousands of lives. If residents of Armero had even an hour's warning, they could have fled to the valley slopes and survived. The mudflows traveled 45 miles (70 km), taking about one and a half hours to get to Armero, so even simple warnings could have saved lives.

Mount St. Helens, 1980, and the Cascades Today

The most significant eruption in the contiguous United States in the past 90 years is that of Mount St. Helens in 1980, a mountain that had lain dormant for 123 years. The volcano is part of the active Cascade volcanic arc, a continental-margin arc built on the western coast of North America above where the minor Juan de Fuca plate is being subducted beneath North America. The arc is relatively small (about 1,200 miles, or 2,000 km, long), and stretches from Lassen Peak in California to Mount Garibaldi in British Columbia. Cascade volcanoes in the United States include Lassen Peak, Mount Shasta, Crater Lake, the Three Sisters, Mounts Jefferson, Hood and Adams, Mount St. Helens, and Mount Rainier. Significant volcanic hazard threats remain from Mount St. Helens, Mount Rainer, and other Cascade volcanoes, especially in the densely populated Seattle area.

Mount St. Helens began to grow above the Cascadia subduction zone about 50,000 years ago, and the volcanic cone that blew up in 1980 formed about 2,500 years ago. Since its birth Mount St. Helens has been one of the most active Cascade volcanoes, erupting on average every 40–140 years. But the largest historical eruption from a Cascade volcano was from the present site of Crater Lake. The volcano Mount Mazama occupied this site about 6,000 years ago but exploded in a cataclysmic eruption that covered much of the Pacific Northwest with volcanic ash. As the crust above the emptied magma chamber collapsed, a giant caldera formed, now occupied by the 2,000-foot (610-m) deep Crater Lake, Oregon. If such a huge volcanic eruption were to occur today in the densely populated Pacific Northwest, the devastating effects would include many thousands of dead. The landscape would be covered with choking ash, rivers would be filled with mudflows, and the global climate would be adversely affected for years.

As the Pacific Northwest became densely settled, the natural areas around Mount St. Helens became popular recreation and tourist sites, attracting many to the beautiful scenery in the area. On March 20, 1980, the mountain rumbled with a magnitude 4.1 earthquake, prompting geologists from the U.S. Geological Survey to install a variety of volcano-monitoring equipment. Automatic cameras, seismographs, tilt meters, gravity meters, and gas collectors were installed to monitor the volcano for any new signs of impending eruption. A variety of precursory warnings of an impending eruption were observed, the most important of which included many swarms of closely spaced small earthquakes known as harmonic tremors and a seismic "humming" of the volcano. The U.S. Geological Survey and Forest Service began to consider volcanic hazards in the area and to propose evacuation routes in case of disaster.

On March 27, 1980, many small eruptions on Mount St. Helens were initiated when magma rose high enough to meet groundwater, which caused steam explosions to reach about two miles (3 km) into the sky. The volcano gradually bulged by about 300 feet (90 m), and harmonic tremors indicated an impending large eruption. By this time several small craters on the volcano's summit had merged to form a single, large crater 1,600 feet (500 m) across and 900 feet (1,600 feet) deep. The U.S. Geological Survey issued eruption warnings, the governor of Washington declared a state of emergency, and the area was evacuated.

The bulge on the volcano continued to grow and the Geological Survey established a volcano-monitoring station six miles (10 km) from the summit, while the state government declared an area around the summit off-limits to all unauthorized personnel.

At 8:32 A.M. on May 18, 1980, the upper 1,313 feet (394 m) of the volcano were blown away in an unusual lateral blast. A magnitude 5.1 earthquake initiated the lateral blast, causing parts of the bulge to collapse and slip away in three separate landslides. The rocks mixed with snow and debris, forming a huge debris avalanche that raced down the mountain at 150 miles per hour (200 km/h) in one of the largest debris avalanches ever recorded. More than a cubic mile (4 km^3) of material moved downhill in the debris avalanche, most of which remained in and around Spirit Lake in layers up to 300 feet (90 m) thick, forming a dam at the outlet of the lake that raised the lake level 200 feet (60 m), doubling its size. The blast from the eruption created a sonic boom heard up to 500 miles (800 km) away in Montana, yet those close to the volcano heard nothing. This is because the sound waves from the eruption initially moved vertically upward and bounced off a warm layer in the atmosphere, returning to spread across the surface at a distance of about 80 miles (130 km) wide around the volcano, leaving a "ring of silence" within the danger zone of the eruption. Some of the sound of the eruption near the blast may also have been absorbed by the huge amounts of ash in the air.

Loss of the weight from the bulge released pressure on the magma inside the volcano, and the side of the mountain exploded outward at 300 miles per hour (500 km/h). The preexisting rock mixed with magma and rose to temperatures of 200°F (93°C). This mass flew into Spirit Lake on the northern flank of the volcano and formed a wave 650 feet (200 m) high that destroyed much of the landscape. Lahars filled the north and south forks of the Toutle River, Pine Creek, and Muddy River. Some of these lahars included masses of ash, mud, and debris, filling much of the Toutle River to a depth of 150 feet (50 m) and locally to as deep as 600 feet (180 m). As the mudflows moved downhill and away from the volcano, they became mixed with more water from the streams and picked up speed as they moved downhill. This prompted a mass evacuation of areas downhill from the volcano, saving countless lives. Vehicles and more than 200 homes were swept away, bridges were knocked out, and the lumber industry was devastated.

A hot pyroclastic flow blasted out of the hole on the side of the volcano and moved at 250 miles per hour (400 km/h), knocking over and burying trees and everything else in its path for hundreds of square miles. The Geological Survey observation post was destroyed and the geologist monitoring the equipment was killed. The forests were a scene of utter devastation after the blast; trees up to 20 feet (6 m) in diameter were snapped at their bases and blown down for miles around, destroying an estimated 3.7 billion board feet (1.3 billion m) of timber. The blast moved so fast that it commonly jumped over ramps in the slope, knocking down trees on the side of a knob facing the volcano, while leaving standing charred remains of the trees that were in the blast shadow hidden behind cliffs on the downwind sides of hills. The wildlife in the forest was virtually wiped out but began to return within a couple of years of the eruption. Remarkably, some of the wildlife that lived underground in burrows or beneath lakes and rocks survived, so some of these resilient beavers, frogs, salamanders, crayfish, as well as some flowers, shrubs, and small trees helped regenerate the ecological systems in the eruption zone.

A huge Plinian ash cloud that erupted to heights of 12 miles (25 km) placed a half billion tons of volcanic ash and debris in the atmosphere. This ash was carried by winds and dropped over much of the western United States. Pyroclastic flows continued to move down the volcano at a rate of 60 miles per hour at temperatures of 550°–700°F (288°–370°C). Sixty-two people died in this relatively minor eruption, and damage to property is estimated at $1 billion. Volcanic ash fell like heavy black rain across much of eastern Washington, Idaho, and Montana. Finer-grained ash that made it into the upper atmosphere managed to circle the globe within 17 days and created spectacular sunsets for months. Even though the amount of ash that fell was relatively minor compared with some other historical eruptions, the ash caused major problems throughout the Pacific Northwest. Planes were grounded, and many electrical transformers short-circuited, while mechanical engines and motor vehicles became inoperable, stranding thousands of people. Breathing was difficult and many had to wear face masks. Rains came and turned the ash layers into a terrible mud that became like concrete, resting heavily on buildings and collapsing roofs.

Smaller eruptions and pyroclastic flows continued to move down the mountain less frequently over the next two years, as a new resurgent dome began to grow in the crater created by the blast that removed the top of the mountain. As the dome grows, residents await the next eruption of a Cascades volcano.

Mount Pinatubo, 1991

The eruption of Mount Pinatubo in the Philippines in 1991 was the second-largest volcanic eruption of the 20th century (after Katmai in Alaska in 1912). It offers many lessons in volcanic prediction, warning, evacuation, and resettlement that may serve as lessons for future eruptions around the world. Pinatubo offers reassuring evidence that careful volcanic monitoring can lead to public warnings and evacuations that can save thousands of lives during catastrophic volcanic eruptions.

Mount Pinatubo is located on the Philippine island of Luzon, about 50 miles (80 km) northwest of Manila and close to what was the U.S. Clark Air Force Base. Before 1991 Mount Pinatubo was known to be a volcano but was not thought to pose much of a threat since it had not erupted for approximately 500 years. About half a million people lived on or near the volcano, including some 16,000 American citizens stationed at Clark Air Force Base. As soon as Pinatubo began to show signs of activity, Philippine and U.S. Geological Survey personnel set up volcano-monitoring stations and equipment, providing detailed and constantly updated evaluations of the status of the volcano and the potential danger levels and likelihood of an impending eruption. Geologists coordinated efforts with local military, civil defense, and disaster-planning officials and quickly worked on determining the volcanic history and mapping areas the most at risk. Critically important was examining the past eruption history to determine how violent past eruptions had been, as an indicator about how bad any impending eruption could be. What the geologists found was frightening, as they determined that Pinatubo had a history of producing tremendous, extremely explosive eruptions, and that such an event might be in the making for the period of activity they were examining. They did not have long to realize their fears.

Precursors to the giant eruption of Pinatubo in June 1991 may have been initiated by a large earthquake on July 16, 1990, centered about 60 miles (100 km) northeast of Pinatubo. This earthquake may have somehow started a series of events that allowed magma to rise beneath the volcano, perhaps opening cracks and fissures beneath the volcano. Soon after this local villagers (known as the Aetas, a seminomadic people who had lived on the volcano for about 400 years, since they fled to the area to hide from conquering Spaniards) reported activity on the mountain, including low rumbling sounds, landslides near the summit, and steam eruptions from fissures. Seismologists measured five small earthquakes around Pinatubo in the next several weeks, but activity seemed to quiet for half a dozen months after the initial swarm of activity.

The first major steam eruption from Pinatubo was observed by villagers, who reported a mile-long (1.6-km) fissure exploding and emitting ash from the north side of the volcano on April 2, 1991. Ash covered surrounding villages, prompting the Philippine Institute of Volcanology and Seismology (PHIVOLCS) and military and civil defense authorities to set up a series of seismographs around the volcano, which recorded more than 200 earthquakes the next day. Authorities declared a volcanic emergency, recommending that villagers within six miles (10 km) of the summit be evacuated. Volcano experts from the U.S. Geological Survey joined the observation and monitoring team on April 23, bringing a plethora of monitoring equipment with them. The local and American teams set up a joint volcano-monitoring Observatory at Clark Air force base, where they also monitored seven seismic stations placed around the volcano.

By the middle of May the Pinatubo Volcano Observatory was recording 30–180 earthquakes a day—at the same time that geologists were scrambling to complete field work to understand the past eruptive behavior of the mountain. The geologists determined that the volcanic basement to the modern peak was about a million years old and that the mountain itself had been built by about six major violent eruptions in the past 35,000 years. They determined that the eruptions were becoming slightly less violent with time but more frequent, with the last major eruption about 500 years ago. The mountain was overdue for a large, violent eruption.

On May 13 volcanologists measured emissions of sulfur dioxide gas, an indicator that molten rock (magma) at depth was rising beneath the volcano. In consultation with the volcano observatory scientists, civil defense authorities issued a series of levels of alerts to warn the public in the event of a catastrophic eruption. These alert levels were updated several times per day, and geologists published new hazard maps showing locations where mudflows, lahars, ash falls, and nuées ardentes were the most likely to occur during an eruption.

Thousands of small earthquakes and greater amounts of sulfur dioxide indicated that magma was still rising beneath the volcano in May, with estimates showing that the magma had risen to within 1.2–4 miles (2–6 km) beneath the surface of the volcano. It was difficult to interpret the warning signs of the impending eruption and to determine whether and when it might occur. The geologists and government officials were torn between ordering immediate evacuations to save perhaps hundreds of thousands of lives, or letting villagers stay until the danger grew more imminent so they could harvest their fields.

On June 1 many of the earthquakes became concentrated in one area beneath a steam vent on the northwest side of the summit, which began to bulge outward. On June 3 the volcano began to spew a series of ash eruptions, which continued to increase such that the volcanic alert level was raised to level three (meaning an eruption was possible within two weeks). About 10,000 villagers were evacuated, and on June 7, the volcano had a minor eruption that sent ash and steam to a height of about five miles (8 km) above the summit. The volcano was bulging more, and there were more than 1,500 earthquakes per day, raising the alert level to four (eruption possible within 24 hours), and the evacuation zone was doubled in distance from the volcano.

June 7 saw a small magma dome oozing out of the volcano about half a mile northwest of its peak, the first sign that magma had reached the surface. Two days later large amounts of sulfur dioxide began to escape again (after having stopped for several weeks), and small nuées ardentes began to tumble down the slopes of the volcano. The volcanic alert was raised to level five—eruption in progress—and massive evacuations began. The ash eruptions grew larger, and on June 10, all aircraft and 14,500 U.S. personnel from Clark Air Force Base left for safer ground at nearby Subic Bay Naval Base, leaving only 1,500 American personnel and three helicopters on the air force base.

At 8:51 A.M. on June 12 the mountain sent huge columns of hot ash surging to 12 miles (20 km) high in the atmosphere, spawning nuées ardentes that covered some now-evacuated villages. Skies became dark and everything for miles around began to be covered with ash. The evacuation radius was increased to 18 miles (30 km) from the volcano, with the numbers of evacuated now reaching approximately 73,000. Eruptions continued, and on June 13, another huge explosion sent ash past 15 miles (25 km) into the atmosphere. Then the volcano became ominously quiet.

Another large eruption broke the silence at 1:09 P.M., followed quickly by a series of 13 more blasts over the next day. Nuées ardentes roared through several more evacuated villages, burying them in hot ash, while typhoon Yunya pelted the area and added wind and rain to the ash, making a miserable mixture. Ash covered the entire region of a thousand square miles. Ash and pumice began falling heavily on Clark Air Force base, and the remaining staff from the volcano observatory fled to a nearby college.

As the scientists were leaving the observatory at Clark, the eruption style changed dramatically for the worse, rapidly moving into the realm of giant eruptions and becoming the second-largest eruption in the world in the 20th century. The cataclysmic eruption continued for more than 9 hours, and during this time more than 90 percent of the material erupted during the whole cycle was blasted into the air. Huge, billowing Plinian ash columns passed 21 miles (34 km) in height and spread across 250 square miles (1,000 km^2). The top of the volcano began to collapse into the empty magma chamber, prompting fears of a truly catastrophic eruption that luckily proved unfounded. The magma was largely drained, and the top of the volcano collapsed into empty space, forming a large caldera whose summit lies 870 feet (265 m) below the former height of 5,724 feet (1,745 m) of the volcano. Ash, nuées ardentes, and lahar deposits hundreds of feet thick filled the valleys draining the flanks of Pinatubo, and thick ash covered buildings across an area of more than 210,000 square miles (340,000 km^2). Approximately five to six cubic miles (20–25 km^3) of volcanic material was blasted from Pinatubo, along with more than 17 megatons of sulfur dioxide 3–16 megatons of chlorine, and upwards of 420,234 megatons of carbon dioxide.

The devastation was remarkable, with buildings wiped away by nuées ardentes and mudflows, and others collapsed by the weight of wet ash on their roofs. Crops were destroyed and roads and canals impassable. Ash covered much of Luzon and fell across the South China Sea, while much ash remained in the atmosphere for more than a year afterward. Smaller eruptions continued, decreasing in frequency through July to about one per day by the end of August, stopping completely on September 4. A new lava dome rose in the caldera a year later in July 1992, but no large eruption ensued. Only between 200 and 300 people died in the initial eruption, although more were to die later in mudflows and other events, bringing the death toll to 1,202. Most of the initial deaths were people who took shelter in buildings whose roofs collapsed under the weight of the rain-soaked volcanic ash.

The well-documented atmospheric effects of the Pinatubo event clearly show the climatic effects of large volcanic eruptions. The gas cloud from Pinatubo, formed from the combination of ash, water, and sulfur dioxide, was the largest cloud of sulfuric acid aerosol since that produced by Krakatau in 1883. This sulfuric acid aerosol eventually reached the ozone layer, where it destroyed huge quantities of ozone and greatly increased the size of the ozone hole over Antarctica. In only three weeks the sulfuric acid cloud spread around the world between 10°S and 30°N latitudes, dropping global temperatures by up to one-half to one degree C and causing spectacular sunsets. The cloud remained detectable in the atmosphere until the end of 1993. Many unusual weather patterns have been attributed to the global lowering of temperatures by the Pinatubo cloud, including colder, wetter, and stormier winters in many locations.

Most of the evacuated villagers lost livestock, homes, and crops, but they survived because of the well-timed warnings and prompt, responsible evacuations by government officials. Conditions in the refugee camps were not ideal, however, and about 350 additional deaths occurred after the eruption from measles, diarrhea, and respiratory infections. The rainy season was approaching, and many mudflows began sweeping down the flanks of the volcano at 20 miles per hour (30 km/hr), then spread across once lush farmland. Hundreds of mudflows were recorded on the eastern flank of the volcano in the last few (rainy) months of 1993, killing another 100 people in 1993 and continued to do so every year after, though with fewer deaths. Mudflow warning systems and alert levels were set up, saving many additional lives in succeeding years.

Economic losses from the eruption of Pinatubo were tremendous, stunting the Philippine economy. Damage to crops and property amounted to $443 million by 1992, with $100 million more spent on refugees and another $150 million on mudflow controls. Eight thousand homes were destroyed, and 650,000 lost jobs for at least several months. The U.S. air and naval bases at Clark and Subic Bay both closed, causing additional job losses in the region.

Mount Pinatubo provided valuable information to geologists and atmospheric scientists about the amount and types of volcanic gases injected into the atmosphere during volcanic eruptions and the effects of these gases on climate and the environment. Most gases in the atmosphere are volcanic in origin, so volcanoes have had a direct link to climate and human activities over geologic time. The relative importance of the release of volcanic gases by volcanoes versus the emission of greenhouse gases by humans in climate change is currently a hotly debated topic. If volcanoes can produce more aerosols and gases in a few days or weeks than humans produce in years, then volcanic eruptions may drastically change the rates of climate change that are produced by natural cycles and human-related emissions.

Gases released from Mount Pinatubo produced an average global cooling around the planet, yet they were also associated with winter warming over the Northern Hemisphere continents for two years following the eruption. These unexpected effects resulted from complex differences in the way the aerosols were distributed in the stratosphere in different places. Aerosol heating in the lower stratosphere combined with a depletion of ozone to contribute to local warming in the Northern Hemisphere winters. The average atmospheric cooling has also been implicated in some biological responses to the volcanic eruption. Coral reefs are very sensitive to small variations in temperature, and after the eruption of Pinatubo coral reefs in the Red Sea saw a massive die-off that was probably related to the atmospheric cooling. The gases in the atmosphere also caused incoming solar radiation to be more diffuse, which led to greater vegetation growth. These additional plants in turn drew a greater amount of carbon dioxide from the atmosphere, further cooling the planet. It has also been hypothesized that Northern Hemisphere winter warming led to a spike in the number of polar bear cubs born the following spring. Most observations and models for atmospheric evolution following massive eruptions show that the aerosol and ozone levels recover to pre-eruption levels within five to 10 years after the eruption.

See also CONVERGENT PLATE MARGIN PROCESSES; MAGMA; PLATE TECTONICS; TSUNAMI, HISTORICAL ACCOUNTS; VOLCANO.

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J

Japan Japan is an island arc and subduction zone trench system that rests as a sliver of the North American plate above the Pacific plate outboard of the Eurasian plate. This tectonic scenario has existed since mid-Tertiary times. From the beginning of the Phanerozoic to the Tertiary, Japan was part of the Eurasian continental margin and was involved in interactions between Eurasia and the Tethys and Panthalassic Oceans. A few occurrences of middle Paleozoic rocks are known from Japan, but the vast majority of strata are younger than middle Paleozoic. Most of the rocks are aligned in strongly deformed structural belts that parallel the coast for 1,850 miles (3,000 km) and include fossiliferous marine strata, weakly to strongly metamorphosed pelitic to psammitic rocks, and granitic intrusions. Since most rocks are strongly deformed in fold-thrust belt structures, one can infer that the more strongly metamorphosed units have been uplifted from deeper in the arc-accretionary wedge system or metamorphosed near the plutons. The complexly deformed zones are overlain by little-deformed Mesozoic-Cenozoic nonmarine to shallow-marine basin deposits. In addition abundant Tertiary volcanic and volcaniclastic deposits are present along the western side of the islands and in the Fossa Magna in central Honshu Island.

In Japan the Sanbagawa belt represents a high-pressure, low-temperature metamorphic belt and the adjacent Ryoke-Abukuma belt represents a high-temperature, low-pressure metamorphic belt. Together these two contrasted metamorphic belts form Japan's paired metamorphic belt. In Japan Akiho Miyashiro (1920–2008) and others deduced in the 1960s that these adjacent belts with contrasted metamorphic histories formed during subduction of the oceanic plates beneath Japan. The low-temperature metamorphic series forms in the trench and immediately above the subduction zone where the cold subducting slab insulates overlying sediments from high mantle temperatures as they are brought down to locally deep high-pressure conditions. These rocks then get accreted to the overriding plate and may

Volcanic vents and sulfur deposits near Kushiro, Hokkaido, Japan, January 1999 *(© Wolfgang Kaehler/CORBIS)*

Mount Fuji and Motosuko Lake in Japan *(Gavin Hellier/Photographers' Choice/Getty Images)*

become exhumed and exposed at the surface in the high-pressure low-temperature belt. Blueschist facies rocks containing the diagnostic mineral galucophane, formed with pressures greater than four kilobars and temperatures between 390°–840°F (200°–450°C), are common.

The adjacent Ryoke-Abukuma belt contains low-pressure high-temperature, as well as medium-pressure, high-temperature metamorphic rocks. These metamorphic rocks form near the axis of the arc in close association with subduction-derived magmas. Since the rocks in this belt form over a considerable crustal thickness and are associated with many high-temperature magmas, they were metamorphosed at a range of pressures and generally high temperatures.

A number of other paired metamorphic belts have been recognized throughout the world. In the western United States the Franciscan complex contains rocks metamorphosed at high pressures and low temperatures, whereas rocks in the Sierra Nevada and Klamath Mountains contain high-temperature, low-pressure metamorphic facies. Other paired metamorphic belts are recognized in Alaska, New Zealand, Indonesia, Chile, Jamaica, and the European Alps.

See also CONVERGENT MARGIN PROCESSES; ISLAND ARCS, HISTORICAL ERUPTIONS; METAMORPHISM AND METAMORPHIC ROCKS.

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Jupiter The fifth planet from the Sun, Jupiter is the gaseous giant of the solar system, named after the most powerful Roman god of the pantheon. It has more than twice the mass of all the other planets combined, estimated at 1.9×10^{27} kilograms, or 318 Earth masses, and a radius of 44,268 miles (71,400 km), or 11.2 Earth radii. Volumetrically it would take 1,400 Earths to fill the space occupied by Jupiter. Jupiter is the third-brightest object in the night sky, following the Moon and Venus. Four of its many moons are visible from the Earth. Orbiting the Sun at a distance of 483 million miles (778 million km, at its semimajor axis), Jupiter takes 11.9 Earth years to complete each orbit.

Visual observations of the surface of Jupiter indicate that the gaseous surface has a rapid differential rotation rate, with the equatorial zones rotating with a period of nine hours and 50 minutes, and higher latitudes rotating with a period of nine hours and 56 minutes. The interior of the planet is thought to be rotating with a period of nine hours 56 minutes, since the magnetic field rotates at this rapid rate. The rapid rotation has distorted the planet so that the equatorial radius (44,365 miles, or 71,400 km) is 6.5 percent greater than the polar radius (41,500 miles, or 66,800 km).

The outer layer of Jupiter is made of gases, with temperatures at the top of the cloud layers estimated to be -127°F (-88°C; 185 k) and a pressure of 10 bars. This is underlain by a layer of molecular hydrogen extending to 12,425 miles (20,000 km) below the surface. The temperature at this depth is estimated to be 19,340°F (11,000°K), with 4 Megabars pressure. Below this a layer of metallic hydrogen extends to 37,280 miles (60,000 km), with basal temperatures of 44,540°F (25,000°K), and 12 Megabars pressure. An internal rocky core extends another 6,215 miles (10,000 km).

Jupiter's surface and atmosphere is visibly dominated by constantly changing colorful bands extending parallel to the equator, and a great red spot, which is a huge, hurricane-like storm. The bands include yellows, blues, browns, tans, and reds, thought to be caused by chemical compounds at different levels of the atmosphere. The most abundant gas in the atmosphere is molecular hydrogen (86.1 percent), followed by helium (13.8 percent). Other chemical elements such as carbon, nitrogen, and oxygen are chemically mixed with helium. Hydrogen is so abundant on Jupiter because the gravitational attraction of the planet is sufficiently large to retain hydrogen, and most of the planet's original atmosphere has been retained.

Since Jupiter has no solid surface layer, the top of the troposphere is conventionally designated as the surface. A haze layer lies above the troposphere, then grades up into the stratosphere. The colorful bands on Jupiter are thought to reflect views deep into different layers of the atmosphere. Several to tens of miles (or kilometers) of white wispy clouds of ammonia ice overlie a layer of red ammonium hydrosulfide ice, then blue water ice extends to about 62 miles (100 km) below the troposphere. The cloud layers constantly change, reflecting different weather and convective systems in the atmosphere, creating the bands and the Great Red Spot. The leading hypothesis about the origin of the bands purports that the light or bright-colored bands are regions where the atmosphere is warm and upwelling, whereas the darker bands are places where the atmosphere is down-welling back to deeper levels. The rapid rotation of Jupiter causes these convective bands to be wrapped around the planet in elongate fashion, unlike on Earth, where they tend to form isolated convective cells. The rotation of the planet causes a strong zonal flow, with most wind belts moving the atmosphere to the east at tens to several hundreds of miles (kilometers) per hour. Several belts are moving westward, with the largest and fastest being the 124-mile-per-hour (200-km/h) westward-moving belt associated with the northern edge of the great red spot. The southern edge of the great red spot is in an eastward-flowing zone (also about 124 miles per hour, or 200 km/h), and the great red spot rotates with the planet, caught between these two powerful belts. Many smaller, oval-shaped vortices that spin off the edges of the Great Red Spot are smaller storms that persist for several or several

Image of Jupiter showing swirling clouds, including the Great Red Spot. This true-color simulated view of Jupiter is composed of four images taken by NASA's *Cassini* spacecraft on December 7, 2000. To illustrate what Jupiter would have looked like if the cameras had a field-of-view large enough to capture the entire planet, the cylindrical map was projected onto a globe. The resolution is about 89 miles (144 km) per pixel. Jupiter's moon Europa is casting the shadow on the planet. Cassini is a cooperative mission of NASA, the European Space Agency, and the Italian Space Agency. JPL, a division of the California Institute of Technology in Pasadena, manages Cassini for NASA's Office of Space Science, Washington, D.C. *(NASA/JPL/University of Arizona)* tens of years. Many similar features are found elsewhere on the planet.

Jupiter has many moons, with the Galilean satellites resembling a miniature solar system. The four largest moons include Io (1.22 Earth/Moon masses), Europa (0.65 Earth/Moon masses), Ganymede (2.02 Earth/Moon masses), and Callisto (1.47 Earth/Moon masses). Each moon is distinct and fascinating, showing different effects of the gravitational attraction of nearby Jupiter. Io and Europa are rocky, planetlike bodies, with Io exhibiting active sulfur-rich volcanism and very young surface material. The energy for the volcanism is thought to be the gravitational attraction of Jupiter, and the sulfur particles emitted from the volcanoes get entrained as charged ions in Jupiter's magnetosphere, forming a plasma torus ring around the planet. Europa has an icy surface with a rocky interior, criss-crossed by cracks on the surface that may be analogous to pressure ridges on terrestrial ice flows. Because the surface does not contain many craters, it must be relatively young. Ganymede and Callisto are icy satellites with low densities, and Ganymede's heavily cratered surface implies maturity. Callisto also has many craters, including two huge ones with multiple rings, reflecting cataclysmic impacts in its history.

See also EARTH; MARS; MERCURY; NEPTUNE; SATURN; SOLAR SYSTEM; URANUS; VENUS.

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K

karst Areas affected by groundwater dissolution, cave complexes, and sinkhole development are called karst terrains. Globally, several regions are known for spectacular karst systems, including the cave systems of the Caucasus, southern Arabia including Oman and Yemen, Borneo, and the mature, highly eroded karst terrain of southern China's Guangxi Province. *Caves* are defined as underground openings and passageways in rock that are larger than individual spaces between the constituent grains of the rock. The term is often reserved for spaces large enough for humans to enter. Many caves are small pockets along enlarged or widened cavities, whereas others are huge open underground spaces. The largest cave in the world is the Sarawak Chamber in Borneo, with a volume of 65 million cubic feet (1.84 million m^3). The Majlis Al Jinn (Khoshilat Maqandeli) Cave in Oman is the second-largest known cave and is big enough to hold several of the sultan of Oman's royal palaces, with a 747 flying overhead (for a few seconds). Its main chamber is more than 13 million cubic feet (370,000 m^3), larger than the biggest pyramid at Giza. Other large caves include the world's third-, fourth-, and fifth-largest caves, the Belize Chamber, Salle de la Verna, and the largest "Big Room" of Carlsbad Cavern, a chamber 4,000 feet (1,200 m) long, 625 feet (190 m) wide, and 325 feet (100 m) high. Each of these has a volume of at least 3 million cubic feet (85,000 m^3). Some caves form networks of linked passages that extend for many miles. Mammoth Cave, Kentucky, for instance, has at least 300 miles (485 km) of interconnected passageways. While the caves are forming, water flows through these passageways in underground stream networks.

The formation of karst topography begins with dissolution. Rainwater that filters through soil and rock works into natural fractures or breaks in the rock, and chemical reactions that remove ions from the limestone slowly dissolve and carry away parts of the limestone in solution. Fractures gradually enlarge, and groundwater flowing in underground stream networks through the rock creates new passageways. Dissolution of rocks is most effective if the rocks are limestone and if the water is slightly acidic (acid rain greatly helps cave formation). Carbonic acid (H_2CO_3) in rainwater reacts with the limestone, rapidly (at typical rates of a fraction of an inch, or a few millimeters per thousand years) creating open spaces, cave and tunnel systems, and interconnected underground stream networks.

When the initial openings become wider, they are known as caves. Many caves are small pockets along enlarged or widened cavities, whereas others are huge, open, underground spaces. In many parts of the world the formation of underground cave systems has led to parts of the surface collapsing into the caverns and tunnels, forming a distinctive type of topography known as karst topography. Karst is named after the Kars Limestone plateau region in Serbia, Bosnia, and Croatia (the southeast part of the former Yugoslavia), where it is especially well developed. Karst topography takes on many forms in different stages of landscape evolution but typically begins with the formation of circular pits on the surface known as sinkholes. These form when the roof of an underground cave or chamber suddenly collapses, bringing everything on the surface suddenly down into the depths of the cave. Striking examples of sinkhole formation surprised residents of Orlando, Florida, in 1981 when a series of sinkholes swallowed many businesses and homes with little warning. In this and many other examples sinkhole formation is initiated after a prolonged drought or drop in groundwater levels. This drains the water from underground cave networks, leaving the roofs of chambers unsupported and making them prone to collapse.

The sudden formation of sinkholes in the Orlando area is best illustrated by the formation of the Winter Park sinkhole on May 8, 1981. The first sign that trouble was brewing was the unusual spectacle of a tree suddenly disappearing into the ground at 7:00 P.M., as if being sucked in by an unseen force. Residents were rightfully worried. Within 10 hours a huge sinkhole nearly 100 feet (30 m) across and more than 100 feet deep had formed. It continued to grow, swallowing six commercial buildings, a home, two streets, six Porsches, and the municipal swimming pool, causing more than $2 million in damage. The sinkhole has since been converted into a municipal park and lake. More than 1,000 sinkholes have formed in parts of southern Florida in recent years, caused by the lowering of the groundwater level to accommodate residential and commercial growth in the region.

Many parts of the world exhibit sinkhole topography: Florida, Indiana, Missouri, Pennsylvania, and Tennessee in the United States, the karst regions of the Balkans, the Salalah region of Arabia, southern China, and many other places where the ground is underlain by limestone.

Sinkholes have many different forms. Some are funnel-shaped, with boulders and unconsolidated sediment along their bottoms; others are steep-walled, pipelike features that have dry or water-filled bottoms. Some sinkholes in southern Oman are up to 900 feet (247 m) deep pipes with caves at their bottoms, where residents obtained drinking water until recently, when wells were drilled. Villagers, mostly women, would have to climb down precarious vertical walls then back out carrying vessels of water. The bottoms of some of these sinkholes are littered with human bones, some dating back thousands of years, of water carriers who slipped on their route. Prehistoric cave art decorates some of the caves, showing that these sinkholes served as water sources for thousands or tens of thousands of years.

Sinkhole formation is intricately linked to the lowering of the water table, as exemplified by the Winter Park example. When water fills the underground caves and passages, it slowly dissolves the walls, floor, and roof of the chambers, carrying the limestone away in solution. When the water table is lowered by drought, by people overpumping the groundwater, or by other mechanisms, the roofs of the caves may no longer be supported, and they may catastrophically collapse into the chambers, forming a sinkhole on the surface. In Florida many of the sinkholes formed because officials lowered the water-table level to drain parts of the Everglades in order to make more land available for development. This ill-fated decision was rethought, and attempts have been made to restore the water table, but in many cases it was too late and the damage was done.

Many sinkholes form suddenly and catastrophically, with the roof of an underground void suddenly collapsing, dropping all of the surface material into the hole. Other sinkholes form more gradually, with the slow movement of loose, unconsolidated material into the underground stream network, eventually leading to the formation of a surface depression that may continue to grow into a sinkhole.

The pattern of surface subsidence resulting from sinkhole collapse depends on the initial size of the cave that collapses, the depth of the cavity, and the strength of the overlying rock. Big caves that collapse can cause a greater surface effect. For a collapsed structure at depth to propagate to the surface, blocks must fall off the roof and into the cavern. The blocks fall by breaking along fractures and falling by the force of gravity. If the overlying material is weak, the fractures will propagate outward, forming a cone-shaped depression with its apex in the original collapse structure. In contrast, if the overlying material is strong, the fractures will propagate vertically upward, causing a pipelike collapse structure.

When the roof material collapses into the cavern, blocks of wall rock accumulate on the cavern floor. There is abundant pore space between these blocks, so the collapsed blocks occupy a larger volume than they did when they were attached to the walls. In this way the underground collapsed cavern can fill completely with blocks of the roof and walls before any effect migrates to the surface. If enough pore space is created, minimal subsidence will occur along the surface. In contrast, if the cavity collapses near the surface, a collapse pit will eventually form on the surface.

Migration of a deep-collapse structure from its initial depth to the surface can take years to decades. The first signs of a collapse structure migrating to the surface include tensional cracks in the soil, bedrock, and building foundations, formed as material pulls away from unaffected areas as it subsides. Circular areas of tensional cracks may enclose an area of contractional buckling in the center of the incipient collapse structure, as bending in the center of the collapsing zone forces material together.

After sinkholes form, they may take on several different morphological characteristics. Solution sinkholes are saucer-shaped depressions formed by the dissolution of surface limestone and have a thin cover of soil or loose sediment. These grow slowly and present few hazards, since they form on the surface and are not connected to underground stream or collapse structures. Cover-subsidence sinkholes form where the loose surface sediments move slowly downward to fill a growing, solution-type sinkhole. Cover-collapse sinkholes form where a thick section of sediment overlies a large solution cavity at depth, and the cavity is capped by an impermeable layer such as clay or shale. A perched water table develops over the aquiclude. Eventually, the collapse cavity becomes so large that the shale or clay aquiclude unit collapses into the cavern, and the remaining overburden rapidly sinks into the cavern, much like sand sinking in an hourglass. These are some of the most dangerous sinkholes, since they form rapidly and can be quite large. Collapse sinkholes are simpler but still dangerous. They form where the strong layers on the surface collapse directly into the cavity, forming steep-walled sinkholes.

Continued maturation of sinkhole topography can lead to the merging of many sinkholes into elongate valleys, and the former surface becomes flat areas on surrounding hills. Even this mature landscape may continue to evolve, until tall, steep-walled karst towers reach to the former land surface, and a new surface has formed at the level of the former cave floor. The Cantonese region of southern China's Guangxi Province best shows this type of karst tower terrain.

Detection of Incipient Sinkholes

Some of the damage from sinkhole formation could be avoided if the location and general time of sinkhole formation could be predicted. At present it may be possible to recognize places where sinkholes may be forming by monitoring for the formation of shallow depressions and extensional cracks on the surface, particularly circular depressions. Building foundations can be examined regularly for new cracks, and distances between slabs on bridges with expansion joints can be monitored to check for expansion related to collapse. Other remote sensing and geophysical methods may prove useful for monitoring sinkhole formation, particularly if the formation of a collapse structure is suspected. Shallow seismic waves can detect open spaces, and ground-penetrating radar can map the bedrock surface and look for collapse structures beneath soils. In some cases it may be worthwhile to drill shallow test holes to determine whether there is an open cavity at depth that is propagating toward the surface.

See also CAVE SYSTEMS, CAVE; SUBSIDENCE.

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Kepler, Johannes (1571–1630) German *Mathematician, Astronomer, Astrologer* Johannes Kepler was a German mathematician and astronomer who became one of the most important and influential scientists of the 17th century for his derivation of the laws of planetary motion. His work contributed to Isaac Newton's theory of gravity, and he helped to confirm the observations of his contemporary Galileo Galilei. In the early 17th century there was no clear distinction between astronomy and astrology, and Kepler also worked with a strong religious conviction that he was exploring and trying to understand a universe created by God according to an intelligent plan that was accessible by reason. Kepler described his own work in astronomy as celestial physics.

EARLY YEARS

Johannes Kepler was born on December 27, 1571, in the imperial free city in what is now the Stuttgart region of Germany. Young Johannes had a rough childhood. His grandfather was mayor of the imperial free city, though the family's riches were declining when he was born, and his father, Heinrich, became a mercenary when Johannes was five. His troubles did not cease, and Heinrich became an alcoholic and abusive parent, leaving the family never to return when Johannes was 16 years old. Historians speculate that his father was killed in the Eighty Years' War in the Netherlands. Johannes was raised by his mother, Katharina Guldenmann, daughter of an innkeeper. Katharina was a healer who practiced herbalism and was by reputation "thin, garrulous, and bad-tempered." She was tried and imprisoned for 14 months for witchcraft and narrowly escaped death by torture. Johannes's grandmother helped with the family, though she was said to be "clever, deceitful, and blazing with hatred." Despite these shortcomings of his upbringing, Johannes's mother brought him outside at the age of six to observe the Great Comet of 1577 and again to witness the lunar eclipse of 1580 at the age of nine.

Johannes also had health problems from an early age. When he was three he contracted smallpox, which left him with impaired vision and crippled hands, so he was deemed unfit for most lines of work and sent to study for the ministry. In his early studies he quickly developed great abilities at mathematics and a keen interest in astronomy. In 1589 Kepler began studying at the University of Tübigen as a theology student, but specializing in astrology and the study of the stars, learning about both the Ptolemaic and the Copernican systems of planetary motion. During this time Kepler became convinced from both theoretical and theological perspectives that the Sun was the center of the universe, not the Earth. With this training and conviction he did not become a minister but was instead appointed to a position of teacher of mathematics and astronomy at the University of Graz (present-day Austria) in April 1594, at age 23. In 1595 Kepler met Barbara Muller, a widow (twice), whose late husbands had left her a fortune. The two were married on April 27, 1597, and the Keplers soon had two children, both of whom died in infancy. They later had other children: a daughter (Susanna) in 1602, and two sons (Friedrich and Ludwig) in 1604 and 1607, respectively.

SCIENTIFIC CONTRIBUTIONS

While lecturing in Graz, Kepler realized that the orbits of Mercury, Venus, Earth, Mars, Jupiter, and Saturn were geometrically regular and corresponded to the same geometric ratios as obtained by nesting the shapes of octahedron, isosahedron, dodedahedron, tetrahedron, and cube inside each other inside a circle. He reasoned that this geometrical regularity could explain the geometrical basis of the universe and used it to support the Copernican system of a Sun-centered solar system in his work *Mysterium Cosmographicum* (The cosmographic universe), published at Tübingen in 1596. Kepler thought he had found God's geometrical plan for the universe and dedicated one chapter of his book to reconciling this idea with biblical passages that most had interpreted to support geocentrism. He published a shorter version of the manuscript, *Mysterium,* later that same year. This was followed by a new edition in 1621, including 25 years of new calculations, notes, and improvements on his earlier work.

Kepler planned four additional books expanding on his ideas in *Mysterium*. These included works on the so-called stationary aspects of the universe (the Sun and fixed stars), one on the planets and their motions, one on the physical nature of planets (including the Earth) and their geographical features, and a fourth on atmospheric optics, meteorology, and astrology. Kepler began corresponding with Danish astronomer Tycho Brahe in letters that discussed their scientific disagreements, but they remained professional and discussed the limits of accuracy of the measurements that Kepler used in his models. In 1600 Kepler went to Prague to work with Brahe, at a time when the financial burden and pressures of his teachings that seemed to go against the church in Graz were forcing him to seek employment elsewhere. Kepler arrived at Benatky nad Jizerou in what would be today the central Czech Republic, where Brahe was building a new observatory and castle, and the two, despite several intense arguments, negotiated a contract for Kepler to work for Brahe. Kepler returned to Graz to collect his family but ran into political difficulties. After refusing to convert to Catholicism, he was banished from Graz and moved to Prague to pursue his work with Brahe, who paid his salary for most of 1601 to work on observations of planetary motions in an attempt to discredit the models of Brahe's (deceased) rival, the mathematician Nicolas Reimers (Ursus). Tycho Brahe unexpectedly died (some rumors suggest that Kepler poisoned him) on October 24, 1601, however, and Kepler was then appointed Brahe's successor as imperial mathematician to Holy Roman Emperor Rudolph II. Kepler was first asked to complete Brahe's unfinished projects, and when Kepler was found to be appropriating Brahe's observations as his own, he encountered difficulties that delayed publication for several years. When this was solved Kepler continued with his productive yet troubled career.

Kepler was in charge of astrology for the emperor, as well as providing advice to him on political issues. But the emperor was incurring financial difficulty, and Kepler often did not get paid on time. Johannes Kepler continued his work on observations of Mars and solar eclipses, and in 1604 he published *Astronomiae Pars Optica* (The optical part of astronomy), including descriptions of the inverse square law of light, reflection of light by different types of mirrors, the principles of pinhole cameras, and observations on optical phenomena such as parallax of stars, where the apparent displacement or difference in orientation of an object when viewed along two different lines of sight is used to calculate the distance to the object. In this book Kepler became the first to recognize that images are projected inversely to the retina by the human eye and had to be corrected "in the hollows of the brain."

Kepler continued his studies of astronomy, including observations of the supernova of 1604, playing down astrological predictions based on the appearance of the new star. He continued to observe and record planetary motions, trying to find a formula that could explain his observations of the orbits and still fit his religious beliefs that the driving power from the Sun, as if a magnetic soul, would decrease with distance from the Sun so the speed of the orbits should decrease with increasing distance from the Sun. Drawing on this, he formulated what would become the second law of planetary motion, that planets sweep out equal areas in equal times. He then tried to fit the orbit of Mars better with his calculations, and after more than 40 failed attempts, he determined that Mars and the other planets followed elliptical orbits. This led to his first law of planetary motion stating that all planets move in ellipses with the Sun as their focus. Kepler wrote these conclusions in his treatise *Astronomia nova* (A new astronomy) in 1605, but legal arguments over his use of Tycho Brahe's measurements as his own prevented publication until 1609.

After Kepler finished *Astronomia nova,* he worked for many years on the *Rudolphine Tables,* which contained ephemerides, or predictions of when certain stars and planets would be found in specific locations. Kepler watched in 1610 as Galileo Galilei announced his discovery of four moons orbiting Jupiter, observed with his powerful new telescope. Kepler endorsed Galileo's observations and later that year published additional observations of the moons of Jupiter in *Narratio de Jovis Satellibus* (Narrative on the satellites of Jupiter).

The year of 1611 was one of misfortune for Kepler. Political tensions forced Emperor Rudolph to abdicate the throne as king of Bohemia to his brother Matthias, who did not favor Kepler. Barbara, Johannes's wife, contracted Hungarian spotted fever, then his three children fell sick with smallpox, and Friedrich, age six, died. Kepler sought new employment but his religious beliefs barred him from returning to the University of Tübingen, so he began to arrange a professorship in Austria. At this time Barbara relapsed into illness and died, then Emperor Rudolph died in 1812. Kepler was so distraught over the tragedies that he was unable to do research, but soon the new king, Matthias, reappointed him as imperial mathematician and allowed him to move to Linz. There Kepler worked on completing the *Rudolphine Tables* and teaching mathematics; he also performed astrological and astronomical services. In 1613 Kepler remarried the young Susanna Reuttinger, and the two had six children, three of whom survived childhood.

In 1615 Kepler completed the first three books of what would be his most influential works, his *Epitome astronomia Copernicanae* (Epitome of Copernican astronomy); the volumes were printed in 1617, 1620, and 1621. These books contained descriptions of the heliocentric model for the universe, the elliptical paths of planets, and all three laws of planetary motion. These laws include the following:

- The orbit of every planet is an ellipse with the Sun at its focus.
- A line joining a planet and the Sun sweeps out equal areas during equal intervals of time.
- The square of the orbital period of a planet is directly proportional to the third power of the semimajor axis of its orbit. Moreover, the constant of proportionality has the same value for all planets.

In addition to these works of science Kepler continued to publish astrological calenders, the payments for which served to pay his bills. These calenders were related to the work Kepler had done on the *Rudolphine Tables* and *Ephemerides* so did not take as much of his time as the *Epitome*. Many of Kepler's astrological predictions were vague, however, and people began to be suspicious, publicly burning his last astrological calender in Graz in 1624.

In one of Kepler's later works, *Harmonices Mundi* (The harmony of the worlds), he first described in detail his third law of planetary motion and attempted to explain the geometrical patterns of the world in terms of music. The *musica universalsi* (music of the spheres) had been described and studied previously by Pythagoras, Ptolemy, and others. Kepler sought out harmonic analysis of regular polygons (all sides of equal length) and regular solids, including the tetrahedron, cube, octahedron, dodecahedron, and icosahedron. The third law of planetary motion was one such harmony, where "the square of the periodic times are to each other as the cubes of the mean distances."

In 1623 Kepler completed his *Rudolphine Tables,* which was printed (after legal battles with Brahe's heir) in 1627. Religious tensions arose again in 1627, when the Catholic Counter Reformation sealed most of Kepler's library and besieged the city of Linz. Kepler and his family fled to Ulm in present-day Germany, where he published his *Rudolphine Tables* at personal expense. In 1628 he became an adviser to General Wallenstein, under Emperor Ferdinand, providing astronomical calculations for the general's astrologers. In this interval Kepler traveled widely, but he became ill and died on November 15, 1630, soon after his family moved to Regensburg, Germany.

See also ASTRONOMY; BRAHE, TYCHO; COPERNICUS, NICOLAUS; GALILEI, GALILEO; LEMAÎTRE, GEORGES.

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L

large igneous province, flood basalt A large igneous province, also known as a continental flood basalt, plateau basalt, and trap, is deposits that include vast plateaus of basalts, covering large areas of some continents. They have a tholeiitic basalt composition, but some show chemical evidence of minor contamination by continental crust. They are similar to anomalously thick and topographically high seafloor known as oceanic plateaus and to some volcanic rifted passive margins. In numerous instances over the past several hundred million years these vast outpourings of lava have accumulated, forming thick piles of basalt, representing the largest-known volcanic episodes on the planet. These piles of volcanic rock represent times when the Earth moved more material and energy from its interior than during intervals between the massive volcanic events. Such large amounts of volcanism also released large amounts of volcanic gases into the atmosphere, with serious implications for global temperatures and climate and may have contributed to some global mass extinctions.

The largest continental flood basalt province in the United States is the Columbia River flood basalt in Washington, Oregon, and Idaho. The Columbia River flood basalt province is 6–17 million years old and contains an estimated 1,250 cubic miles (4,900 km^3) of basalt. Individual lava flows erupted through fissures or cracks in the crust, then flowed laterally across the plain for up to 400 miles (645 km).

The 66-million-year-old Deccan flood basalts, also known as traps, cover a large part of western India and the Seychelles. They are associated with the breakup of India from the Seychelles during the opening of the Indian Ocean. Slightly older flood basalts (90–83 million years old) are associated with the breakaway of Madagascar from India. The volume of the Deccan traps is estimated to be 5 million cubic miles (20,840,000 km^3). This huge volume of volcanic rocks erupted over a period of about 1 million years, starting slightly before the great Cretaceous-Tertiary extinction. Most workers now agree that the gases released during the flood basalt volcanism stressed the global biosphere to such an extent that

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Map of the world showing distribution of flood basalts

Columbia River flood basalts along Snake River Birds of Prey National Conservation Area near Boise, Idaho *(David R. Frazier/Photo Researchers, Inc.)*

many marine organisms had gone extinct, and many others were stressed. Then the planet was hit by the massive Chicxulub impact, causing the massive extinction that included the end of the dinosaurs.

The breakup of east Africa along the East African rift system and the Red Sea is associated with large amounts of Cenozoic (fewer than 30 million years old) continental flood basalts. Some of the older volcanic fields are located in east Africa in the Afar region of Ethiopia, south into Kenya and Uganda, and north across the Red Sea and Gulf of Aden into Yemen and Saudi Arabia. These volcanic piles underlie younger (fewer than 15-million-year-old) flood basalts that extend both farther south into Tanzania and farther north through central Arabia, where they are known as Harrats, and into Syria, Israel, Lebanon, and Jordan.

An older volcanic province, the North Atlantic Igneous Province, also associated with the breakup of a continent, formed along with the breakup of the North Atlantic Ocean at 62–55 million years ago. The North Atlantic Igneous Province includes both onshore and offshore volcanic flows and intrusions in Greenland, Iceland, and the northern British Isles, including most of the Rockall Plateau and Faeroe Islands. The opening of the ocean in the south Atlantic is similar to 129–134-million-year-old flood basalts, which, now split in half, comprise two parts. In Brazil the flood lavas are known as the Paraná basalts, and in Namibia and Angola of west Africa, as the Etendeka basalts.

These breakup basalts are transitional to submarine flood basalts that form oceanic plateaus. The Caribbean Ocean floor is one of the best examples of an oceanic plateau, with other major examples including the Ontong-Java Plateau, Manihiki Plateau, Hess Rise, Shatsky Rise, and Mid-Pacific Mountains. All of these oceanic plateaus contain between six- and 25-mile (10–40-km) thick piles of volcanic and subvolcanic rocks, representing huge outpourings of lava. The Caribbean seafloor preserves five- to 13-mile (8–21-km) thick oceanic crust formed before about 85 million years ago in the eastern Pacific Ocean. This unusually thick ocean floor was transported eastward by plate tectonics, where pieces of the seafloor collided with South America as it passed into the Atlantic Ocean. Pieces of the Caribbean oceanic crust are now preserved in Colombia, Ecuador, Panama, Hispaniola, and Cuba, and some scientists estimate that the Caribbean oceanic plateau was once twice its present size. In either case it represents a vast outpouring of lava that would have been associated with significant outgassing, with possible consequences for global climate and evolution.

The western Pacific Ocean basin contains several large oceanic plateaus, including the 20-mile (32-km) thick crust of the Alaskan-sized Ontong-Java Plateau, the largest outpouring of volcanic rocks on the planet. Having formed in two intervals, at 122 and 90 million years ago, respectively, entirely within the ocean, the Ontong-Java Plateau represents magma that rose in a plume from deep within the mantle and erupted on the seafloor. Estimates suggest that the volume of magma erupted in the first event was equivalent to that of all the magma being erupted at midocean ridges at the present time. Sea levels rose by more than 30 feet (9 m) in response to this volcanic outpouring. The gases released during these eruptions are estimated to have raised average global temperatures by 23°F (13°C).

ENVIRONMENTAL HAZARDS OF FLOOD BASALT VOLCANISM

The environmental impact of the eruption of large volumes of basalt in provinces including those described above can be severe. Huge volumes of sulfur dioxide, carbon dioxide, chlorine, and fluorine are released during large basaltic eruptions. Much of this gas may get injected into the upper troposphere and lower stratosphere during the eruption process, being released from eruption columns that reach two to eight miles (3–13 km) in height. Carbon dioxide is a greenhouse gas and can cause global warming, whereas sulfur dioxide and hydrogen sulfate have the opposite effect: they can cause short-term cooling. Many of the episodes of volcanism preserved in these large igneous provinces were rapid, repeatedly releasing enormous quantities of gases over periods of fewer than 1 million years, and releasing enough gas to change the climate significantly and more rapidly than organisms could adapt. For instance, one eruption of the Columbia River basalts is estimated to have released 9 billion tons of sulfur dioxide and thousands of millions of tons of other gases, whereas the eruption of Mount Pinatubo in 1991 released about 20 million tons of sulfur dioxide.

The Columbia River basalts of the Pacific Northwest continued erupting for years at a time, for approximately 1 million years. During this time the gases released would be equivalent to that of Mount Pinatubo every week, maintained for decades to thousands of years at a time. The atmospheric consequences are sobering. Sulfuric acid aerosols and acid from the fluorine and chlorine would form extensive poisonous acid rain, destroying habitats and making waters uninhabitable for some organisms. At the very least the environmental consequences would be such that organisms were stressed to the point that they would be unable to handle an additional environmental stress, such as a global volcanic winter and subsequent warming caused by a giant impact.

Faunal extinctions have been correlated with the eruption of the Deccan flood basalts at the Cretaceous-Tertiary (K/T) boundary, and with the Siberian flood basalts at the Permian-Triassic boundary. There is still considerable debate about the relative significance of flood basalt volcanism and impacts of meteorites for extinction events, particularly at the Cretaceous-Tertiary boundary. Most scientists would now agree, however, that global environment was stressed shortly before the K/T boundary by volcanic-induced climate change, and then a huge meteorite hit the Yucatán Peninsula, forming the Chicxulub impact crater and causing the massive K/T boundary extinction and the death of the dinosaurs.

The Siberian flood basalts cover a large area of the Central Siberian Plateau northwest of Lake Baikal. They are more than half a mile thick over an area of 210,000 square miles (543,900 km^2) but have been significantly eroded from an estimated volume of 1,240,000 cubic miles (3,211,600 km^3). They were erupted over an extraordinarily short period of fewer than 1 million years, 250 million years ago, at the Permian-Triassic boundary. They are remarkably coincident in time with the major Permian-Triassic extinction, implying a causal link. The Permian-Triassic boundary at 250 million years ago marks the greatest extinction in Earth history, when 90 percent of marine species and 70 percent of terrestrial vertebrates became extinct. It has been postulated that the rapid volcanism and degassing released enough sulfur dioxide to cause a rapid global cooling, inducing a short ice age with associated rapid fall of sea level. Soon after the ice age took hold, the effects of the carbon dioxide took over and the atmosphere heated to cause global warming. The rapidly fluctuating climate postulated to have been caused by the volcanic gases is thought to have killed off many organisms, which were simply unable to cope with the wildly fluctuating climate extremes.

See also IGNEOUS ROCKS; MASS EXTINCTIONS; OCEANIC PLATEAU.

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lava Molten rock or magma that flows on the surface of the Earth is known as lava. Lavas have a wide range in composition, texture, temperature, viscosity, and other physical properties, based on the composition of the melt and the amount of volatiles present. They tend to be very viscous (sticky, resistant to flow) when they are rich in silica and form slow-moving and steep-sided flows. The addition of a large amount of volatiles to silicic magma can cause explosive eruptions. Mafic, or low-silica, lavas are less viscous and tend to flow more easily, forming planar flows with gently sloping surfaces. Some basaltic flood lavas have flowed over hundreds or thousands of square miles (square kilometers), forming flat-lying layers of crystallized lava. Other mafic and intermediate lavas form shield volcanoes such as the Hawaiian Islands, with gently sloping sides built by numerous eruptions. If mafic lavas are rich in volatiles, they tend to become abundant in empty gas bubbles known as vesicles, forming pumice. Mafic lavas that flow on the surface often form ropey lava flows known as pahoehoes, or blocky flows known as aa lavas.

Some types of lava flows are extremely hazardous whereas others may be relatively harmless if treated with caution. In the most passive types of volcanic eruptions lava bubbles up or effuses from volcanic vents and cracks and flows like thick water across the land surface. During other eruptions lava oozes out more slowly, producing different types of flows with different hazards. Variations in magma composition, temperature, dissolved gas content, surface slope, and other factors lead to the formation of three main different types of lava flows. These include aa, pahoehoe, and block lava. Aa are characterized by a rough surface of spiny and angular fragments, whereas pahoehoe have smooth, ropeylike or billowing surfaces. Block lavas have larger fragments than aa flows and are typically formed by stickier, more silicic (quartz rich) lavas than aa and pahoehoe flows. Some flows are transitional between these main types, or may change from one type to another as surface slopes and flow rates change. Pahoehoe

Lava flow crossing Chain of Craters road from the west toward Hiiaka crater during eruption of Kilauea Volcano, Hawaii, May 5, 1973 *(R.L. Christiansen/USGS)* flows commonly change into aa flows with increasing distance from the volcanic source.

Lava flows are most common around volcanoes that are characterized by eruptions of basalt with low contents of dissolved gasses. About 90 percent of all lava flows worldwide are made of magma with basaltic composition, followed by andesitic (8 percent) and rhyolitic (2 percent). Places with abundant basaltic flows include Hawaii, Iceland, and other exposures of oceanic islands and midoceanic ridges, all characterized by nonexplosive eruptions. Virtually the entire volume of all the islands of the Hawaiian chain are made of a series of lava flows piled high one on top of the other.

Lava flows generally follow topography, flowing from the volcanic vents downslope in valleys, much as streams or water from a flood would travel. Some lava flows move as fast as water, up to almost 40 miles per hour (65 km/hour) on steep slopes, but most lava flows move considerably more slowly. More typical rates of movement range from about 10 feet per hour (several meters per hour) to 10 feet (3 m) per day for slower flows. These rates of lava movement allow most people to move out of danger to higher ground, but lava flows are responsible for significant amounts of property damage in places like Hawaii. Lava flows have buried roads, farmlands, and other low-lying areas. One must keep in mind, however, that the entire Hawaiian Island chain was built by lava flows, and the real estate that is being damaged would not even exist if it were not for the lava flows. In general pahoehoe flows are the fastest, aa are intermediate, and blocky flows are the slowest.

Basaltic lava is extremely hot (typically about 1,830°–2,100°F, or 1,000°–1,150°C) when it flows across the surface, so when it encounters buildings, trees, and other flammable objects, they typically burst into flame and are destroyed. More silicic lavas are slightly cooler, in the range of 1,560°–1,920°F (850°–1050°C). Most lavas will become semisolid and stop flowing at temperatures approaching 1,380°F (750°C). Lavas cool quickly at first, until a crust or hard skin forms on the flow, then they cool more slowly. This property of cooling creates one of the greatest hazards of lava flows. A lava flow that appears hard, cool, and safe to walk on can hide an underlying thick layer of molten lava at temperatures of about 1,380°F (750°C) just below the thin surface. Many people have mistakenly thought it was safe to walk across a recent crusty lava flow, only to plunge through the crust to a fiery death. Thick flows take years to crystallize and cool, and residents of some volcanic areas have learned to use the heat from flows for heating water and piping it to nearby towns.

See also IGNEOUS ROCKS; VOLCANO.

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Lawson, Andrew Cooper (1861–1952) Scottish *Geologist* Andrew Cooper Lawson is known for his work in isostasy and the geology of western North America. He was born July 25, 1861, in Anstruther, Scotland, but moved with his family to Hamilton, Ontario, Canada, at age six. He studied in public schools in Hamilton and later received a bachelor's degree in natural sciences in 1883 from the University of Toronto and a master of arts degree in natural sciences from the same university in 1885. He then received another master's degree and a doctorate in geological sciences from the Johns Hopkins University in 1888. Lawson then spent seven years with the Geological Survey of Canada until he moved to the University of California at Berkeley, where he remained for 60 years until his death on June 16, 1952. During this time his studies of isostasy, the relative vertical movements of the crust and balance between crust and mantle rocks, continued over three decades, and these studies brought special attention to the importance of isostasy in deformation of the Earth's crust. He also developed the logical consequences of isostatic adjustment as an important factor in orogenesis. In some cases this was seen as the determinative agent in the elevation of mountains and the depression of deep troughs and basins. His research areas included the Sierra Nevada, the Great Valley of California, the Mississippi delta, the Cordillera, and the Canadian shield. Lawson also spent about 40 years studying the northwest region of Lake Superior, where he provided new information and revised the correlation of the pre-Cambrian rocks over a large part of North America.

His earlier studies of Lake of the Woods and Rainy Lake showed that the Laurentian granites were intrusive into metamorphosed volcanic and sedimentary rocks that he called the Keewatin Series. Under this series he found another sedimentary series that he called Coutchiching and saw this as the oldest rocks in the series. Later research on this area showed that two periods of batholithic invasion were followed by a great period of peneplaination. These surfaces, the Laurentian peneplain and the Eparchean peneplain, were used as references for the correlation of the invaded formations and for the subsequently deposited sedimentary beds over the areas. Lawson also worked as a consultant in a number of construction engineering projects including San Francisco's Golden Gate Bridge.

During his work in California Lawson became the first to identify and name the San Andreas Fault in 1895, and later, after the 1906 San Francisco earthquake, he was the first to map the entire length of the fault. Lawson is most famous for being the editor and coauthor of the 1908 report on the 1906 earthquake, a report that later became known as the Lawson Report.

See also GEOPHYSICS; LITHOSPHERE; NORTH AMERICAN GEOLOGY.

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Lemaître, Georges (1894–1966) Belgian *Cosmologist* Georges Lemaître is most famous for proposing the theory of the big bang in 1933. He was born July 17, 1894, in Charleroi, Belgium, where he studied civil engineering and obtained a Ph.D. for his dissertation, "L'Approximation des fonctions de plusieurs variables réelles" (Approximation of functions of several real variables). He was ordained in 1923 as a Catholic priest before moving to Cambridge, United Kingdom, to study astrophysics at St. Edmund's College. He then moved to the United States, where at the Massachusetts Institute of Technology, he became fascinated by Edwin Hubble's observations of an expanding universe and discussed this with Harvard University astronomer Harlow Shapley, who also advocated an expanding-universe model. He extrapolated the consequences of an expanding universe back in time and proposed the model of the big bang for the origin of the universe. Lemaître became a professor of astrophysics at the University of Louvain, Belgium, in 1927.

Georges Lemaître was a brilliant mathematician and cosmologist who pioneered the application of Albert Einstein's theory of general relativity to cosmology, publishing a precursor to Hubble's law in 1927 in the *Annales de la Société Scientifique de Bruxelles* (*Annals of the Scientific Society of Brussels*), entitled "Un Univers homogène de masse constante et de rayon croissant rendant compte de la vitesse radiale des nébuleuses extragalactiques" (A homogeneous universe of constant mass and growing radius accounting for the radial velocity of extragalactic nebulae). His next major paper hypothesized a big bang origin for the universe in a paper that was published in the prestigious journal *Nature* in 1931. He proposed that the universe started much like an incredibly dense egg or "primal atom" in which all the material for the entire universe was compressed into a sphere about 30 times larger than the Sun. Being an ordained priest, he noted the similarity of the big bang model to the "creation" of the universe in biblical accounts. In his models published in 1933 and 1946 he estimated that the primal atom exploded to create the universe, some 20 billion to 60 billion years ago. This model was widely criticized at first, in part for resembling too much the biblical account of creation, and proposed by a priest at that. Eventually, in 1933 Einstein endorsed Lemaître's theory, and at a meeting in California Einstein said of the theory, "This is the most beautiful and satisfactory explanation of creation to which I have ever listened." The scientific world listened, tested the theory, and soon the big bang theory became the leading model for the origin of the universe.

Lemaître soon became world renowned and was widely heralded as the leader of the new cosmological physics. In 1934 King Leopold III of Belgium awarded Lemaître the Francqui Prize, the highest Belgian scientific and scholarly prize, awarded to scientists under the age of 50 and named after Belgian diplomat and businessman Emile Francqui. In 1941 Lemaître was elected to the Royal Academy of Science and Arts of Belgium, and in 1953 he became the first recipient of the Eddington Medal, bestowed by the Royal Astronomical Society. In 1936 he was elected to the Pontifical Academy of Sciences and was president of this organization from 1960 until his death on June 20, 1966.

See also ASTRONOMY; ASTROPHYSICS; COSMIC MICROWAVE BACKGROUND RADIATION; DARK MATTER; HUBBLE, EDWIN; ORIGIN AND EVOLUTION OF THE UNIVERSE.

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life's origins and early evolution The origin of life and its early evolution from simple, single-celled organisms to more complex forms has intrigued scientists, philosophers, theologians, and others from all over the world for much of recorded history. The question of the origin of life relates to where humans came from, why people are here, and what the future holds for the species. One of the most interdisciplinary of sciences, the study of the origin of life encompasses cosmology, chemistry, astrophysics, biology, geology, and mathematics.

The scientific community has supported several ideas about the location of the origin of life. Some scientists believe that life originated by chemical reactions in a warm little pond, whereas others suggest that it may have started in surface hot springs. Another model holds that the energy for life was first derived from deep within the Earth, at a hydrothermal vent on the seafloor. Still others hold that life may have fallen to Earth from outer reaches of the solar system, though this does not answer the question of where and how it began.

Life on the early Earth would have to have been compatible with conditions very different from what they are on the present-day Earth. The Earth's early atmosphere had very little if any oxygen, so the partial pressure of oxygen was lower and the partial pressure of carbon dioxide (CO_2) was higher in the early Archean. The Sun's luminosity was about 25 percent less than that of today, but since the early atmosphere was rich in CO_2, CH_4 (methane), NH_3 (ammonia), and N_2O (nitrous oxide), an early greenhouse effect warmed the surface of the planet. CO_2 was present at about 100 times its current levels, so the surface of the planet was probably hotter than today, despite the Sun's decreased luminosity. Evidence suggests that the surface was about 140°F (60°C), favoring thermophilic bacteria (heat adaptive) over organisms that could not tolerate such high temperatures. The lack of free oxygen and radiation-shielding ozone (O_3) in the early atmosphere led to a 30 percent higher ultraviolet flux from the Sun, which would have been deadly to most early life. The impact rate from meteorites was higher and heat flow from the interior of the Earth was about three times higher than at present. Early life would have to have been compatible with these conditions, so it would have to have been thermophilic and chemosynthetic (meaning early life-forms had the metabolic means for synthesizing organic compounds using energy extracted from reduced inorganic chemicals). The best place for life under these extreme conditions would be deep in the ocean. The surface would have been downright unpleasant.

Since the Earth is cool today, some process must have removed CO_2 from the atmosphere, otherwise it would have had a runaway greenhouse effect, similar to that on the planet Venus. Processes that remove CO_2 from the atmosphere include deposition of limestone ($CaCO_3$) and burial of organic matter. These processes are aided by chemical weathering of silicates (e.g., $CaSiO_3$) by CO_2-rich rainwater that produces dissolved Ca^{2+}, SiO_2, and bicarbonate (HCO_3^-), which is then deposited as limestone and silica. Life evolved in the early Precambrian and began to deposit organic carbon, removing CO_2 from the atmosphere. Limestones that formed as a result of organic processes acted as large CO_2 sinks and served to decrease global temperatures.

The present-day levels of CO_2 in the atmosphere are balanced by processes that remove CO_2 from the atmosphere and processes that return CO_2 to the atmosphere. Today sedimentary rocks store 78,000 billion tons of carbon, a quantity that would have required a few hundred million years to accumulate from the atmosphere. The return part of the carbon cycle is dominated by a few processes. The decomposition of organic matter releases CO_2. Limestone deposited on continental margins is eventually subducted, or metamorphosed, into calc-silicate ($CaSiO_3$) rocks, both processes that release CO_2. This system of CO_2 cycling regulates atmospheric CO_2, and thus global temperature on longtime scales. Changes in the rates of carbon cycling are intimately associated with changes in rates of plate tectonics, showing that tectonics, atmospheric composition and temperature, and the development of life are closely linked in many different ways.

Recognizing signs of life in very old, deformed rocks is often difficult. Searching for geochemical isotope fractionation is one method or detecting signs of previous life in rocks. Metabolism produces distinctive isotopic signatures in carbon (C)—organic and inorganic carbon 13/carbon 12 isotope ratios differ by about 5 percent. So the presence of isotopically light carbon in old rocks suggests the influence of life. Diverse forms of life—photosynthesizing, methanogenic, and methylotropic organisms may all have been present 3.5 or even 3.85 billion years ago. Early life, in a preoxygen-rich atmosphere, had to be adapted to the reducing environment.

Life 3.8 billion years ago consisted of primitive prokaryotic organisms (unicellular organisms that contain no nucleus and no other membrane-bound organelles). These organisms made their own organic compounds (carbohydrates, proteins, lipids, nucleic acids) from inorganic carbon derived from CO_2, water, and energy from the Sun by photosynthesis, but they did not release molecular oxygen (O_2) as a by-product. More familiar photosynthetic organisms use water (H_2O) as the reducing agent, oxidizing it to O_2 in a process called oxygenic photosynthesis. In contrast, many of these early prokaryotic organisms used hydrogen sulfide (H_2S) as their electron donors, producing elemental sulfur in a process called anoxygenic photosynthesis. The sulfur could then be further oxidized to form sulfate ions (SO_4^{2-}). Oxygen would have been toxic to these prokaryotes and the environment would have been devoid of oxygen. Because of this, they obtained their energy through anaerobic cellular respiration rather than aerobic respiration, reducing sulfate ions rather than O_2. By 3.5 Ga, cyanobacteria, a type of bacteria formerly called blue-green algae that are capable of oxygenic photosynthesis, used CO_2 and emitted O_2 to the atmosphere. As a result the protective ozone (O_3) layer began to form, blocking ultraviolet (UV) radiation from the Sun and making the surface habitable for other organisms.

Ophiolites that are 2.5 billion years old with black smoker types of hydrothermal vents and evidence for primitive life-forms have been discovered in northern China. The physical conditions at these and even older midocean ridges permit the inorganic synthesis of amino acids and other prebiotic organic molecules, and this environment would have been sheltered from early high levels of UV radiation and its harmful physical effects on biomolecules. In this environment the locus of precipitation and synthesis for life might have been in small, iron-sulfide globules emitted by hydrothermal vents on

THE SEARCH FOR EXTRATERRESTRIAL LIFE

Ever since humans turned their eyes skyward and realized that the billions of stars out there are similar to the Earth's Sun, they wondered if there might be other forms of life in the universe. This speculation has run the range from deep philosophical and religious thought, to science fiction, through scientific investigation of the likelihood of other life existing beyond Earth. There are two main theories on the origin of extraterrestrial life, if any exists at all. One is that different life-forms may have risen independently in separate locations within the universe and be completely unrelated to each other. Another theory, called panspermia, suggests that life originated in one place, then spread to other habitable planets. Either or both theories could be true, although it is also possible that neither is true since no extraterrestrial life has ever been documented.

Spacecraft launched by NASA have contained messages intended as a welcome to any intelligent life-forms that may encounter them and wish to contact the Earth. The *Voyager 1* spacecraft launched September 5, 1977, to probe the outer solar system and beyond contained two golden records with sound and images intended to portray the diversity of life and culture on Earth. The *Galileo* spacecraft, launched by NASA October 18, 1989, to study Jupiter and its moons also contained an apparatus to search for possible extraterrestrial life, particularly on the moon Europa, which contains a saltwater ocean beneath a layer of ice. The American astronomer Carl Sagan (1934–96) devised a set of experiments using Galileo's instruments to test for possible life using remote sensing. Sagan made a list of criteria needed to identify life on another planet system using remote sensing, and this became known as the "Sagan criteria for life." Included are the following:

- strong absorption of light at the red end of the visible spectrum (especially over continents), which was caused by absorption by chlorophyll in photosynthesizing plants
- absorption bands of molecular oxygen that is also a result of plant activity, infrared absorption bands caused by the ~1 micromole per mole (μmol/mol) of methane in the Earth's atmosphere (molecular oxygen is a gas that must be replenished by either volcanic or biological activity)
- modulated narrowband radio wave transmissions uncharacteristic of any known natural source

The Mars *Rover* mission, launched by NASA in 2003, placed two mobile rovers on the surface of Mars with the primary aim of searching for evidence that liquid water once existed on the surface of Mars. Water is essential for life as we know it, and if evidence of water could be found then it would be possible that life once evolved there. The Mars *Rovers* did find abundant evidence for past episodes of water flowing across the surface of the red planet, but so far, no direct evidence of life has been documented.

Search for Extra-Terrestrial Intelligence (SETI) is the collective name for a number of activities to detect intelligent extraterrestrial life. The SETI Institute is a research institute dedicated to the search for extraterrestrial intelligence. Their mission is to explore, understand, and explain the origin, nature, and prevalence of life in the universe. The institute employs over 150 scientists in three separate cen-the seafloor. Extant prokaryotic organisms, including both archaeans and bacteria, currently inhabit black smoker chimneys near the East Pacific Rise, at 230°F (110°C), the highest-known temperature at which life exists on the Earth. Life at these black smokers and other similar environments draws energy from the internal energy of the Earth (not the Sun) via oxidation in a reducing environment.

Life apparently remained relatively simple for more than a billion years. Roughly 2.5 billion years ago some prokaryotic life-forms evolved into eukaryotes, organisms whose cells contain nuclei and other membrane-bound organelles. Molecular biology yields some clues about life at 2.5 Ga. Molecular phylogenies compare genetic sequences and show that all living species cluster into three domains, Archea, Bacteria, and Eukarya (which includes plants, animals, protists, and fungi). They all have a common ancestor that is thermophilic, or heat-loving. The deepest branches of the "universal tree of life" are dominated by heat-loving species. This amazing fact suggests that hydrothermal systems provided the location for the origin and development of early life. The oldest thermophiles are all chemosynthetic organisms that use hydrogen (H) and sulfur (S) as major constituents in their metabolic processes. H and S are readily available at the black smoker chimneys, adding further support to the idea that submarine hydrothermal vents may have been the site of the development of Earth's earliest life.

Late Archean (2.5 Ga) banded-iron formations (BIFs) associated with the Dongwanzi, Zunhua, and Wutai Shan ophiolites in North China have black smoker chimneys associated with them, and some of

ters, the Center for SETI Research, the Carl Sagan Center for the Study of Life in the Universe, and the Center for Education and Public Outreach. Sponsors of research in the center include NASA, the U.S. Department of Energy, U.S. Geological Survey, Argonne National Laboratory, University Space Research Association, and many others.

The Center for SETI Research seeks evidence of intelligent life in the universe through signatures of its technologies. To this end scientists in the center have developed signal-processing technologies to search for signals of intelligent life in the cosmos. This includes the development of new signal-processing algorithms and the analysis of data collected from radio telescopes and other observational media. One of the most sophisticated instruments for collecting data and searching for signals from any possible extraterrestrial intelligence is the Allen telescope array, consisting of an array of 350 radio telescopes spread across one hectare, being constructed at the Hat Creek Radio Observatory 290 miles northeast of San Francisco. This radio interferometry telescope array will be dedicated 24 hours per day, seven days a week, to the search for signals from extraterrestrial technologies.

The Sagan Center for the Study of Life in the Universe is an astrobiology research center whose focus is to examine a wide variety of problems such as modeling the precursors of life on the Earth and in the depths of outer space and to investigate how life began and how its many forms evolved and survived different conditions. At the Sagan Center, scientists ask questions like How many planets are there that might support life? What is required for life to exist? How did life evolve, and what is the range of forms possible? and How many intelligent forms of life may exist in the universe? The Sagan Center obtains its funding from NASA, the National Science Foundation, and major universities.

One way of estimating the likelihood of the existence of extraterrestrial life in the universe is called the Drake equation, named after University of California Santa Cruz astronomer Frank Drake. The Drake equation multiplies estimates of the following terms together:

- the rate of formation of suitable stars
- the fraction of those stars that link with planets
- the number of Earth-like worlds per planetary system
- the fraction of planets where intelligent life develops
- the fraction of possible communicative planets
- the "lifetime" of possible communicative civilizations

Using these parameters, Drake estimated that there are about 10,000 planets in the Milky Way Galaxy that contain intelligent life and have the possibility of communicating with the Earth. Extrapolating this equation beyond the Milky Way Galaxy, scientists estimate that there are 125 billion galaxies in the universe. If 10 percent of all Sun-like stars have a planetary system, and if even only one thousandth of 1 percent of all stars are like the Sun, and there are about 500 billion stars in each galaxy, then there are about 6.25×10^{18} stars that have planets orbiting them in the universe. If one out of 1 billion of these stars has a planet that supports life, then there could be 6.25 billion planets with life-forms on them in the universe. Thus, intelligent life may be out there.

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Burgess Shale Paleozoic landscape showing opabinia, hallucigenia, wiwaxia, and pikaia *(Publiphoto/Photo Researchers, Inc.)*

these bear signs of early life. This was a time when the Earth's surface environment began a dramatic shift from reducing environments to highly oxidizing conditions. This may be when photosynthesis first developed in sulfur-reducing bacteria. Oxygenic photosynthesis first developed in cyanobacteria, later transferred to plants (eukaryotes) through an endosymbiotic association.

Life continued to have a major role in controlling atmospheric composition and temperature for the next couple of billion years. The first well-documented ice age occurred at the Archean-Proterozoic boundary, although some evidence points to other ice ages in the Archean. The Archean-Proterozoic ice age may have been related to decreasing tectonic activity and to less CO_2 in the atmosphere. Decreasing plate tectonic activity resulted in less CO_2 released by metamorphism and volcanism. These trends resulted in global levels of atmospheric CO_2 falling, and this in turn caused a less effective greenhouse, enhancing cooling, and leading to the ice age.

Prolonged cool periods in the Earth history are called ice houses. Most result from decreased tectonic activity and the formation of supercontinents. Intervening warm periods are called hot houses, or greenhouses. In hot house periods, higher temperatures cause more water vapor to be evaporated and stored in the atmosphere, so more rain falls during hot houses than in normal times, increasing the rates of chemical weathering, especially of calcium silicates. These free Ca and Si ions in the ocean combine with atmospheric CO_2 and O_2, to form limestone and silica that gets deposited in the oceans. This increased removal of CO_2 from the atmosphere, in turn, cools the planet in a self-regulating mechanism. The cooling reduces the rate of chemical weathering. Previously deposited calc-silicates are buried and metamorphosed, and they release CO_2, which counters the cooling from a runaway ice age effect, warming the planet in another self-regulating step.

The earliest bacteria appear to have been sulfate-reducing thermophilic organisms that dissolved sulfate by reduction to produce sulfide. In this process the bacteria oxidize organic matter, transferring the electrons to sulfur and leading to the release of CO_2 into the atmosphere and the deposition of FeS_2 (pyrite), which became massive sulfide deposits in the ocean sediments.

BIFs are rocks rich in iron and silica that are common in 2.2 to 1.6-Ga old rock sequences. They are the source of 90 percent of the world's iron ore. BIFs were probably deposited during a hot house interval and require low oxygen in the atmosphere/hydrosphere system to form. Scientists have hypothesized that water with high concentrations of Fe^{2+} was derived from weathering of crust.

Eukaryotes with membrane-bound cell nuclei emerged at about 2 Ga. Aerobic photosynthetic cells evolved and very effectively generated oxygen. These organisms rapidly built up atmospheric oxygen, to high levels by 1.6 Ga. The eukaryotes evolved into plants and animals. For the next billion years oxygen increased and CO_2 fell in the atmosphere until the late Proterozoic, when the explosion of invertebrate metazoans (jellyfish) marked the emergence of complex Phanerozoic styles of life on the Earth. This transition occurred during the formation and breakup of the supercontinent of Gondwana, with associated climate changes from a 700-Ma global ice house (supercontinent), with worldwide glaciations, to equatorial regions. This was followed by warmer climates and rapid diversification of life.

See also ARCHEAN; BLACK SMOKER CHIMNEYS; CARBON CYCLE; CLOUD, PRESTON; COMET; FOSSIL; HISTORICAL GEOLOGY.

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lithosphere The top of the mantle and the crust of the Earth is a relatively cold and rigid boundary layer called the lithosphere, which is typically about 60 miles (100 km) thick. Heat escapes through the lithosphere largely by conduction, transport of heat in igneous melts, and convection cells of water through midocean ridges. The lithosphere is about 75 miles (125 km) thick under most parts of continents, and 45 miles (75 km) thick under oceans, whereas the asthenosphere extends to about a 155-mile (250-km) depth. Lithospheric roots, also known as the tectosphere, extend to about 155 miles (250 km) beneath many Archean cratons.

The base of the crust, known as the Mohorovicic discontinuity (the Moho), is defined seismically and reflects the rapid increase in seismic velocities from basalt to peridotite at five miles per second (8 km/s). Petrologists distinguish between the seismic Moho, as defined above, and the petrologic Moho, reflecting the difference between the crustal cumulate ultramafics and the depleted mantle rocks from which the crustal rocks were extracted. This petrological Moho boundary is not recognizable seismically. In contrast, the base of the lithosphere is defined rheologically as where the same rock type on either side begins to melt, and it corresponds roughly to the 2,425°F (1,330°C) isotherm, or line in two dimensions and plane in three dimensions, along which temperatures have the same value.

Since the lithosphere is rigid, it cannot convect. It loses its heat by conduction and has a high temperature contrast (and geothermal gradient) across it compared with the upper mantle, which has a more uniform temperature profile. The lithosphere thus forms a rigid, conductively cooling thermal boundary layer riding on mantle convection cells, becoming convectively recycled into the mantle at convergent boundaries.

The elastic lithosphere is that part of the outer shell of the Earth that deforms elastically, and the thickness of the elastic lithosphere increases significantly with the time from the last heating and tectonic event. This thickening of the elastic lithosphere is most pronounced under the oceans, where the elastic thickness of the lithosphere is essentially zero to a few miles (or kilometers) at the ocean ridges. The lithosphere increases in thickness proportionally to the square root of age to about a 35-mile (60-km) thickness at an age of 160 million years.

One can also measure the thickness of the lithosphere by the wavelength and amplitude of the flexural response to an induced load. The lithosphere behaves in some ways like a thin beam or ruler on the edge of a table that bends and forms a flexural bulge inward from the main load. The wavelength is proportional to and the amplitude is inversely proportional to the thickness of the flexural lithosphere under an applied load, providing a framework to interpret the thickness of the lithosphere. Natural loads include volcanoes, sedimentary prisms, thrust belts, and nappes. The load of mountains on the edges of continents tends to deflect the underlying lithosphere into a bulge with an amplitude of typically 1,000 feet (300 meters) and a wavelength several hundred miles long. In contrast, oceanic crust exhibits shorter wavelength and higher amplitude bulges, because oceanic lithosphere is not as stiff or flexurally rigid as oceanic crust. Typically the thermal, seismic, elastic, and flexural thicknesses of the lithosphere are different because each method is measuring a different physical property, and also because elastic and other models of lithospheric behavior are overly simplistic.

See also ASTHENOSPHERE; CONTINENTAL CRUST; CRATON; OPHIOLITES; PLATE TECTONICS.

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Lyell, Sir Charles (1797–1875) Scottish *Geologist* In the early 1830s Sir Charles Lyell authored the pioneering work *Principles of Geology*, a textbook that propelled uniformitarianism into the geological mainstream and is now considered a classic in the field. With this single influential work he firmly established geology as a science by convincing geologists to study the present in order to learn about the past. Since one cannot directly observe past processes, one must compare the results of those processes (such as fossils, mountains, and lavas) with modern geological phenomena currently forming by observable processes. Though the theme of *Principles* was not novel, Lyell reintroduced Scottish geologist James Hutton's ideas with a preponderance of supporting evidence that he gathered during numerous geological excursions across Europe and North America. He also dared to profess that humans were much older than creationists believed and named several geological eras: Eocene, Miocene, and older and newer Pliocene.

PREFERENCE OF GEOLOGY OVER LAW

Charles Lyell was the oldest of 10 siblings, born November 14, 1797, at the family estate, Kinnordy, at Kirriemuir, in the county of Angus, Scotland. His mother's maiden name was Frances Smith, and his father, Charles senior, was a wealthy lawyer who enjoyed collecting rare plants. His family moved to Hampshire, England, when Charles was an infant. At the age of seven he was sent to the first of several English schools and graduated at the top of his class in June 1815. When he was 11 he suffered a bout of pleurisy, and while recovering he began insect collecting, using his father's books to identify the various species. Entomology (the study of insects) spawned a more general interest in the natural sciences that persisted throughout his life.

Lyell entered Exeter College, Oxford University in January 1816 to study Greek, Latin, and the writings of Aristotle. Having already read Robert Bakewell's *Introduction to Geology* (1813), he was anxious to attend the mineralogy and geology lectures given by William Buckland. The English geology professor was a neptunist, meaning he supported the theories of the German geologist Abraham Gottlob Werner, who proposed the then commonly accepted idea that all rocks on the Earth were formed from a vast, ancient ocean that completely covered the planet and shaped the structure of its surface with its swirling, turbulent waters. While at Oxford Lyell began making geological excursions, a practice that continued throughout his lifetime. In 1817 he studied the column-shaped formations of basalt on the island of Staffa, Scotland. German geologist Leopold von Buch had proposed that Fingal's Cave on Staffa was formed by erosion of a dike of soft lava, but Lyell observed that the basalt columns of the cave's roof had broken ends, demonstrating Buch's theory to be false. While traveling to France, Switzerland, and Italy with his family in 1818, Lyell witnessed the effect of glaciers in the Alps and recognized an age sequence in the succession of rock exposures he observed.

In 1819 Lyell became a fellow of both the Geological Society and the Linnean Society of London. In December of that year he received a bachelor of arts degree in the classics from Oxford University. At his father's request Lyell entered Lincoln's Inn to study law, but he continued to study geology. He was admitted to the bar in 1822, but poor eyesight caused his eyes to swell and hurt frequently and made legal reading difficult for him. The Geological Society elected him joint secretary in 1823 and thus demonstrated that he was accepted as a geologist by his peers.

UNIFORMITARIANISM

Lyell visited Paris that year and met several famous scientists including Georges Cuvier, Alexander von Humboldt, and Constant Prévost. The alternating layers of marine and freshwater formations in the Paris basin intrigued Lyell, and he realized that minor changes in a geological barrier could explain the pattern. In 1824 Lyell accompanied Buckland on a trip through Scotland during which he pondered the Parallel Roads of Glen Roy, admired the granite veins of Glen Tilt, and studied limestone and marl deposits in small freshwater lakes in Bailie. He read his first paper to the Geological Society in December of that year, "On a Recent Formation of Freshwater Limestone in Forfarshire," followed by more on Tertiary exposures of the Hampshire coast of England. In 1826 an article he published in the *Quarterly Review,* "Transactions of the Geological Society of London," summarized the current knowledge and major areas of investigation in geology. While composing this review, he began to believe that ordinary geological forces such as earthquakes and volcanoes could explain unusual phenomena such as the presence of sedimentary strata formed on the ocean floor but found on mountain summits. The Royal Society of London elected Lyell a fellow in 1826.

Lyell continued to make geological excursions, including trips to France, Italy, and Scotland, collecting data wherever he visited. One journey in 1828 that affected his views about geological processes brought him to France, Germany, and Italy with Scottish geologist Roderick Murchison. In central France Lyell found analogies between the geological past and formations currently developing. Again, he thought modern processes must resemble those that had shaped ancient formations. The revelation struck him that the appearance of strata was determined by the conditions when it was laid, not just by age. Similar conditions in the present day could replicate a layer with characteristics in common with an ancient stratum; thus modern conditions and geological processes must resemble those of the past.

In Italy he observed layers of lava exposed in the mountain walls of Etna, fossils of living species buried at its base, and younger uplifted strata with large percentages of extant species. These observations led to his conclusion that the volcanic mountain had been formed relatively recently, layer by layer. Accruing evidence caused him to doubt the neptunist doctrine, and he observed more physical support for the vulcanists, who believed that volcanic activity was responsible for the major changes in the construction of the Earth's surface. Cuvier believed that life on the Earth was periodically destroyed through the violent actions of catastrophic events such as floods. Lyell rejected this idea of catastrophism. Instead he believed that geological changes were caused gradually by ordinary geological processes, a theory called uniformitarianism, proposed by Scottish geologist James Hutton in 1785. Lyell believed that the steady accumulation of changes from earthquakes and volcanic activity caused the elevation and disturbances found in the sedimentary rocks. He imagined that geological processes he directly observed also occurred in the past, forming analogous structures.

PRINCIPLES AND ELEMENTS

Geologists of the time were prepared to reject Werner's ideas for Hutton's, but they needed a push. They were ready to accept that basalt was of igneous origin but more hesitant to accept uniformity of geological processes of the past and the present and of uniform gradual rates of change. Lyell published *Principles of Geology: An Attempt to Explain the Former Changes in the Earth's Surface by Reference to Causes Now in Operation,* which appeared in three volumes between 1830 and 1833 and is now considered a classic in geology. The theme of the first volume was Hutton's uniformitarianism, for which Lyell clearly presented substantial geological reasoning. His arguments urged scientists to explain geological phenomena by comparison with modern processes and conditions. By studying modern occurrences, one could gain a better understanding of the past. He reviewed the processes of erosion, sediment accumulation, volcanic activity, and uplifting by earthquakes. Change was gradual, and even major changes in the Earth's surface structure could result from the buildup of relatively subtle changes over a sufficient period of time.

The second volume of *Principles of Geology* focused on organic evolution—the change over geological time in the populations of living species, a process that Lyell considered to be fixed. Lyell stated that as former species became extinct, new distinct species emerged to maintain a continuous, natural balance. Later he altered his views on organic evolution, agreeing with Darwin that life-forms have evolved from primitive into more complex forms over time. Extinction resulted from changes in an environment's physical characteristics as well as from dynamic relationships with other species in an ecosystem. Lyell made no claims concerning the mechanism by which new species emerged.

The beginning of the third volume addressed criticisms of his first two volumes. The remainder described the application of uniformitarianism and modern analogies to geological research and presented Lyell's classification scheme of the Tertiary formations that lay just below the most recent sedimentary deposits. (The Tertiary period spans the interval from 66 to 1.8 million years ago.) He identified the species of embedded fossil shells, figured out how many of the species were still living (extant), and declared the rock beds containing lower percentages of living species to be older than the ones containing more living species. This method was relative but served its purpose. He sorted the rock formations into epochs, Eocene (the oldest), Miocene, and the older and newer Pliocene (the most recent), and suggested that as time progressed, newer species replaced those driven to extinction by geological change. This volume included an appendix that contained tables of more than 3,000 Tertiary fossil shells.

King's College in London appointed Lyell professor of geology in 1831, and the general public attended his lectures in great numbers. He held this position for only two years, preferring not to have commitments outside his own research. Lyell married Mary Elizabeth Horner on July 12, 1832, and they set up a home in London. Fluent in German and French, Mary traveled with him and a translated for him. The couple had six daughters. As Lyell's eyes degenerated with age, his wife read to him and took dictation from him.

Revising and adding to his *Principles of Geology,* which had 12 editions in his lifetime, kept Lyell busy until his death. One significant change in its 10th edition (1867–68) was the modification of the entire text to incorporate Darwin's evolutionary theory that suggested natural selection as the mechanism of action. In 1838 Lyell published an introductory geology textbook for students, *Elements of Geology,* which had six editions. (Editions three, four, and five were titled *A Manual of Elementary Geology*).

EXPERTISE ABROAD

In 1841 the Lyells traveled to the United States for the first time. Lyell delivered a series of lectures at the Lowell Institute in Boston and explored the geology of the Atlantic coast. He was not a polished lecturer, but his engagements were always filled to capacity with those interested in his vision of the planet in ancient times. While touring North America he estimated the rate of recession of Niagara Falls toward Lake Erie, studied the Tertiary formations on the coasts of Virginia, the Carolinas, and Georgia, explored the Ohio Valley, Lake Erie, and Lake Ontario, examined coal in Nova Scotia, and visited an earthquake site in New Madrid, Missouri. In 1845 he published *Travels in North America,* then returned to deliver the Lowell lectures, explore the South including the coalfields in Alabama, investigate the growth of the delta of the Mississippi River, and collect fossils. After publishing *A Second Visit to the United States of North America* (1849), he returned again in 1852 and 1853.

Lyell traveled to Madeira and the Canary Islands in the Atlantic Ocean from 1853 to 1854 to study volcanic geology. Buch had proposed the craters of elevation theory to explain the formation of volcanic islands such as Tenerife and Palma (of the Canary Islands). He thought that volcanoes were formed by the horizontal solidification of lava, followed by violent upheaval incomparable to any modern-day geological processes, and then the collapse of masses of Earth, forming tent-like roofs over large conical caverns. From his visit to France in 1828 Lyell recalled the intact cones and craters of extinct volcanoes and the unbroken sheets of lava extending from the cones in the Auvergne. In 1859 Lyell again visited the sheets of hardened rock on the slopes of Mount Etna and Mount Vesuvius in Italy and found no center of upheaval as would be predicted by Buch's proposed mechanism. In addition he had seen modern lavas solidifying on 15–20 degree angled slopes on Madeira and Palma. On Etna he witnessed lavas solidifying on slopes of up to 40 degrees. In 1858 he published "On the Structure of Lavas Which Have Consolidated on Steep Slopes; With Remarks on the Mode of Origin of Mount Etna, and on the Theory of Craters of Elevation," a paper that invalidated the theory of craters of elevation.

THE AGE OF MAN

Analysis of the flora and fauna of the Canary Islands in addition to the species's geographical distribution induced Lyell to ponder the question of the origin of species. In 1856 further discussions with Darwin prepared him to accept with certainty the process of species evolution. Acceptance that species could evolve into new species forced Lyell to consider the prehistory of humans. Scientists were uncovering paleontological evidence that suggested humans had been around much longer than believed at the time. A human skeleton with apelike features was discovered in Neanderthal, Germany, in 1857, and in 1859 a man-made tool was found embedded in ancient river gravel in France in a location previously believed to be much older than humans. These developments were too important simply to add into new editions of *Elements* or *Principles,* so Lyell composed a new work, *The Geological Evidences of the Antiquity of Man.* The book summarized substantial data for the evolution, or gradual change, in all species and provided evidence that humans had evolved from other animal species over a long period of time. Though Darwin had published *On the Origin of Species* in 1859, he had specifically omitted any discussion on the origin of humans, saving this discussion for his 1871 book, *The Descent of Man.* The former led to much controversy concerning the evolution of humans, however, and Lyell avoided stating a clear conclusion on the matter, leaving readers to draw their own conclusions based on the presented evidence. The blatant omission upset Darwin, who had developed a close friendship with Lyell. The following year Lyell publicly declared his full support for Darwin's theory of indefinite modification of species by means of natural selection and completely revised the 10th edition of *Principles* to reflect this.

KNIGHTHOOD AND BARONETCY

Lyell's wife, Mary, died of typhoid fever in 1873. Lyell's own health had begun to fail in 1869. He died on February 22, 1875, and was buried in Westminster Abbey. Considered a classic in geology today, Lyell's *Principles of Geology* was just as popular during the 19th century, evidenced by the fact that Lyell had just finished writing the 12th edition at the time of his death. Queen Victoria conferred knighthood on Lyell in 1848 and made him a baronet in 1864. He had served as president of the Geological Society from 1834 to 1836 and again in 1849, and president of the British Association for the Advancement of Science in 1864. The Royal Society of London awarded him both the Royal Medal (1834) and the Copley Medal (1858), and the Geological Society awarded him the Wollaston Medal (1866). At his request the Lyell Medal was established in 1875 and is awarded annually by the Geological Society. He also made provisions for the disbursement of money from the Lyell Geological Fund to support the geological sciences.

British geologist and biographer Edward Bailey sums up Lyell's enduring contribution to the field of geology in *Charles Lyell*: "He did more than anyone else to free geology from the authority of tradition. He steadfastly sought truth through deduction from observation." *Principles of Geology* exerted a profound influence on geologists of the time by shifting the focus away from catastrophism to uniformitarianism, but Lyell affected scientists in other areas as well. Biologist Charles Darwin was heavily influenced by the idea of gradual change over time and applied it to his proposed theory of evolution by means of natural selection.

See also DARWIN, CHARLES; EVOLUTION; HISTORICAL GEOLOGY; HUTTON, JAMES; STRATIGRAPHY, STRATIFICATION, CYCLOTHEM; WERNER, A. G.

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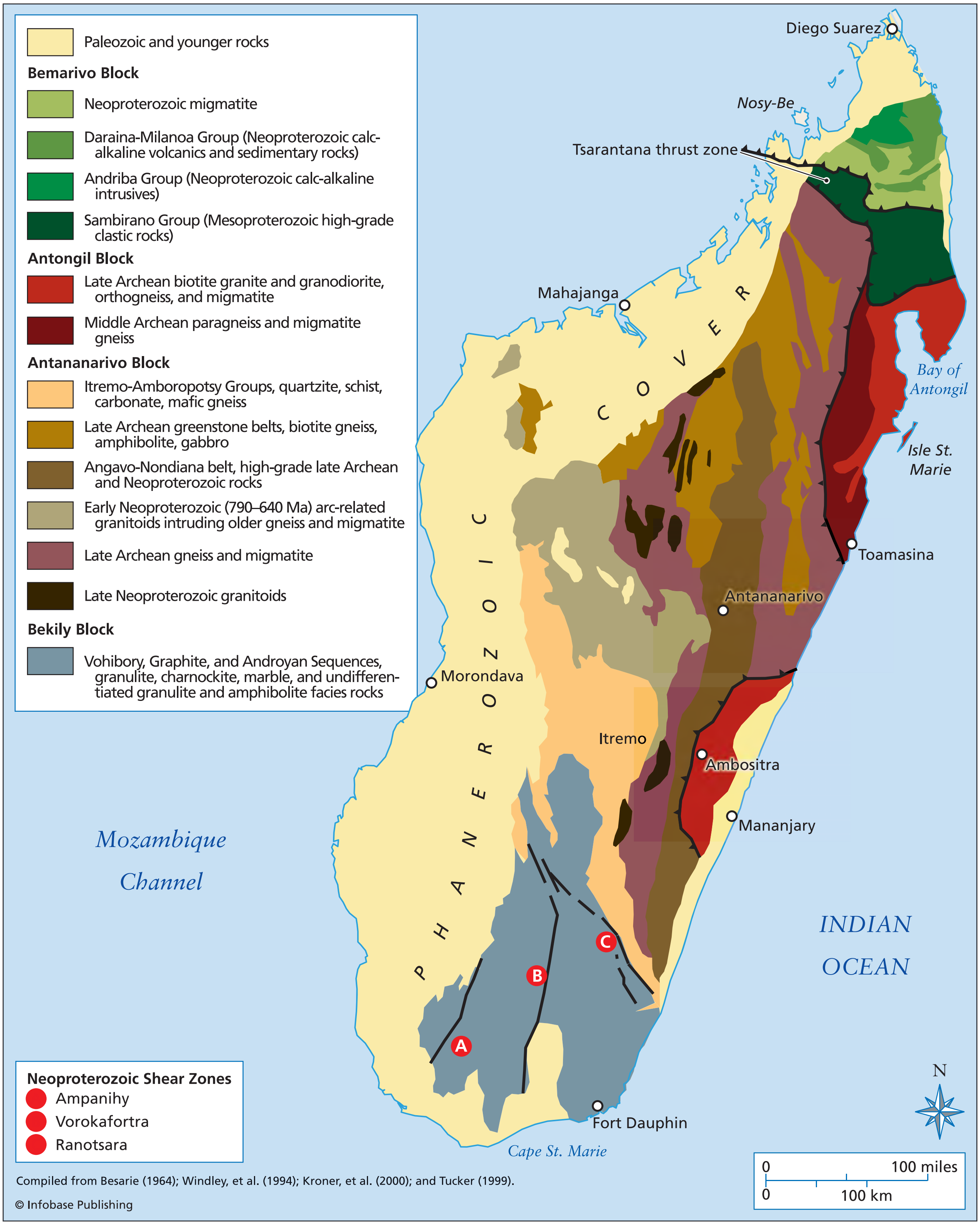
Madagascar Madagascar is the world's fourth largest island, covering 388,740 square miles (627,000 km^2) in the western Indian Ocean off the coast of southeast Africa. Madagascar consists of a highland plateau fringed by a lowland coastal strip on the east, with a very steep escarpment dropping thousands of feet from the plateau to the coast over a distance of only 50–100 miles (80.5–161 km). Madagascar was separated from Africa by continental drift, and so is geologically part of the African mainland. The highest point in Madagascar is Mount Maromokotro in the north, which rises to 9,450 feet (2,882 m); the Ankaratra Mountains in the center of the plateau rise to 8,670 feet (2,645 m). The plateau dips gently to the western coast of the island toward the Mozambique Channel, where wide beaches are located. Several islands surround the main island, including Isle St. Marie in the northeast and Nosy-Be in the north. Most of the high plateau of Madagascar was once heavily forested, but intense logging over the last century has left most of the plateau a barren, rapidly eroding soil and bedrock-covered terrain. Red soil eroded from the plateau has filled many of the river estuaries along the coast.

Precambrian rocks underlie the eastern two-thirds of Madagascar, and the western third of the island is underlain by sedimentary and minor volcanic rocks that preserve a near complete record of sedimentation from the Devonian to Recent. The Ranotsara fault zone divides the Precambrian bedrock of Madagascar into two geologically different parts. The northern part is underlain by Middle and Late Archean orthogneisses, variably reworked in the Early and Late Neoproterozoic, whereas the southern part, known as the Bekily Block, consists dominantly of graphite-bearing paragneisses, bounded by north-south trending shear zones that separate belts with prominent fold-interference patterns. All rocks south of the Ranotsara fault zone have been strongly reworked and metamorphosed to granulite conditions in the latest Neoproterozoic. Because the Ranotsara and other sinistral fault zones in Madagascar are subvertical, their intersections with Madagascar's continental margin provide ideal piercing points to match with neighboring continents in the East African Orogen. Thus, the Ranotsara fault zone is considered an extension of the Surma fault zone or the Ashwa fault zone in East Africa, or the Achankovil or Palghat-Cauvery fault zones in India. The Palghat-Cauvery fault zone changes strike (orientation relative to geographic north) to a north-south direction near the pre-breakup position of the India-Madagascar border and continues across northern Madagascar. The Precambrian rocks of northern Madagascar can be divided into three north-south trending tectonic belts defined, in part, by the regional metamorphic grade. These belts include the Bemarivo Block, the Antongil Block, and the Antananarivo Block.

The Bemarivo Block of northernmost Madagascar is underlain by calc-alkaline intrusive igneous rocks (Andriba Group) with geochemical compositions suggestive of rapid derivation from depleted mantle sources. These rocks are strikingly similar in age, chemistry, and isotopic characteristics to the granitoids of the Seychelles and Rajasthan (India). The Andriba granitoids are overlain by the Daraina-Milanoa Group (~750–714 million years old) in the north, and juxtaposed against the Sambirano Group in the south. A probable collision zone separates the Sambirano Group from the Andriba Group. The Daraina-Milanoa Group consists of two parts: a lower, largely clastic metasedimentary sequence and an upper volcanic sequence dominated by andesite with lesser basalt and rhyolite. Like the Andriba Group, volcanic rocks of the Daraina-Milanoa Group are calc-alkaline in chemistry and have geochemical signatures indicating that these rocks were derived directly from melting in the mantle. Copper (Cu) and



Compiled from Besarie (1964); Windley, et al. (1994); Kroner, et al. (2000); and Tucker (1999).

Geological map of Madagascar showing the distribution of Precambrian rocks and shear zones in the east and the Paleozoic basins in the west gold (Au) mineralization occurs throughout the belt. The Sambirano Group consists of pelitic schist, and lesser quartzite and marble, which are variably metamorphosed to greenschist grade (in the northeast) and amphibolite grade (in the southwest). In its central part, the Sambirano Group is invaded by major massifs of migmatite gneiss and charnockite. The depositional age and provenance of the Sambirano Group is unknown.

The Antongil Block, surrounding the Bay of Antongil and Isle St. Marie, consists of late Archean biotite granite and granodiorite, migmatite, and tonalitic and amphibolitic gneiss, bounded on the west by a belt of Middle Archean metasedimentary gneiss and migmatite. These tonalitic gneisses of this region are the oldest rocks known on the island of Madagascar, dated using radiometric methods to be 3.2 billion years old. The older gneisses and migmatites are intruded by circa 2.5 billion-year-old epidote-bearing granite and granodiorite. Late Archean gneisses and migmatites near the coast in the Ambositra area may be equivalent to those near the bay of Antongil, although geochronological studies are sparse and have not yet identified middle Archean rocks in this area. Rocks of the Antongil Block have greenschist to lower-amphibolite metamorphic assemblages, in contrast to gneisses in the Antananarivo Block which tend to be metamorphosed to granulite facies. This suggests that the Antongil Block may have escaped high-grade Neoproterozoic events that affected most of the rest of the island. Gneisses in this block are broadly similar in age and lithology to the peninsular gneisses of southern India. High-grade psammites of the Sambirano Group unconformably overlie the northern part of the Antongil Block, and become increasingly deformed toward the north in the Tsarantana thrust zone, a Neoproterozoic or Cambrian collision zone between the Bemarivo Block and central Madagascar. The western margin of the Antongil Block is demarcated by a 30-mile (50-km) wide belt of pelitic metasediments with tectonic blocks of gabbro, harzburgite, and chromitites, with nickel and emerald deposits. This belt, named the Betsimisiraka suture, may mark the location of the closure of a strand of the Mozambique Ocean that separated the Antongil Block (and southern India?) from the Antananarivo Block within the Gondwanan supercontinent.

The Antananarivo Block is the largest Precambrian unit in Madagascar, consisting mainly of 2.55–2.49 billion-year-old granitoid gneisses, migmatites, and schist intruded by 1,000–640 million-year-old calc-alkaline granites, gabbro, and syenite. Rocks of the Antananarivo Block were strongly reworked by high-grade Neoproterozoic tectonism between 750 and 500 million years ago, and metamorphosed to granulite facies. Large, sheet-like granitoids of the stratoid series intruded the region, perhaps during a phase of extensional tectonism. Rocks of the Antananarivo Block were thrust to the east on the Betsimisiraka suture over the Antongil Block between 630–515 million years ago, then intruded by post-collisional granites (such as the 537–527 million-year-old Carion granite, and the Filarivo and Tomy granites) between 570–520 million years ago.

The Sèries Quartzo-Schisto-Calcaire or QSC (also known as the Itremo Group) consists of a thick sequence of Mesoproterozoic stratified rocks comprising, from presumed bottom to top, quartzite, pelite, and marble. Although strongly deformed in latest Neoproterozoic time (~570–540 million years ago), the QSC is presumed to rest unconformably on the Archean gneisses of central Madagascar because both the QSC and its basement are intruded by Early Neoproterozoic (~800 million-year-old) granitoids and no intervening period of tectonism is recognized. The minimum depositional age of the QSC is ~800 million years ago, and its maximum age, of ~1,850 million years ago, is defined by U-Pb detrital zircon geochronology. The QSC has been variably metamorphosed (~570–540 million years ago; greenschist grade in the east; amphibolite grade in the west) and repeatedly folded and faulted, but original sedimentary structures and facing-directions are well preserved. Quartzite displays features indicative of shallow subaqueous deposition, such as flat lamination, wave ripples, current ripple cross lamination, and dune cross-bedding, and carbonate rocks have preserved domal and pseudo-columnar stromatolites. To the west of the Itremo Group, rocks of the Amboropotsy and Malakialana Groups have been metamorphosed to higher grade, but include pelites, carbonates, and gabbro that may be deeper water equivalents of the Itremo Group. A few areas of gabbro/amphibolite-facies pillow lava/marble may represent strongly metamorphosed and dismembered ophiolite complexes.

Several large greenstone belts crop out in the northern part of the Antananarivo Block. These include the Maevatana, Andriamena, and Beforana-Alaotra greenstone belts, collectively called the Tsarantana sheet. Rocks in these belts include metamorphosed gabbro, mafic gneiss, tonalites, norite, and chromitites, along with pelites and minor magnetite-iron formation. Some early intrusions in these belts have been dated by Robert Tucker of Washington University in St. Louis to be between 2.75 and 2.49 billion years old, with some 3.26 billion-year-old zircon xenocrysts and Middle Archean neodymium (Nd) isotopic signatures. The chemistry, age, and nature of chromite mineralization all suggest an arc setting for the mafic rocks of the Tsarantana sheet, which is in thrust contact with underlying gneisses of the Antananarivo Block. The thrust zone is not yet well documented, but limited studies indicate east-directed thrusting. Gabbro intrusions that are 800–770 million years old cut early fabrics, but are deformed into east-vergent asymmetric folds cut by east-directed thrust faults.

The effects of Neoproterozoic orogenic processes are widespread throughout the Antananarivo Block. Archean gneisses and Mesoproterozoic stratified rocks are interpreted as the crystalline basement and platformal sedimentary cover, respectively, of a continental fragment of undetermined tectonic affinity (East or West Gondwanan, or neither). This continental fragment (both basement and cover) was extensively invaded by subduction-related plutons in the period from about 1,000 to ~720 million years ago, which were emplaced prior to the onset of regional metamorphism and deformation. Continental collision related to Gondwana's amalgamation began after ~720 million years ago and before ~570 million years ago and continued throughout the Neoproterozoic with thermal effects that lasted until about 520 million years ago. The oldest structures produced during this collision are kilometer-scale fold-and-thrust nappes with east or southeast-directed vergence (present-day direction). They resulted in the inversion and repetition of Archean and Proterozoic rocks throughout the region. During this early phase of convergence, warm rocks were thrust over cool rocks, thereby producing the present distribution of regional metamorphic isograds. The vergence of the nappes and the distribution of metamorphic rocks are consistent with their formation within a zone of west- or northwest-dipping continental convergence (present-day direction). Later upright folding of the nappes (and related folds and thrusts) produced kilometer-scale interference fold patterns. The geometry and orientation of these younger upright folds is consistent with east-west horizontal shortening (present-day direction) within a sinistral transpressive regime. This final phase of deformation may be related to motion along the Ranotsara and related shear zones of south Madagascar and to the initial phases of lower crustal exhumation and extensional tectonics within greater Gondwana.

South Madagascar, known as the Bekily Block, consists of upper amphibolite and higher-grade paragneiss bounded by north-south-striking shear zones that separate belts with prominent fold interference patterns. Archean rocks south of the Ranotsara shear zone have not been positively identified but certain orthogneisses have Archean ages (~2.9 billion years) that may represent continental basement to the paragneisses of the region. All rocks south of the Ranotsara shear zone have been strongly reworked and metamorphosed in the latest Neoproterozoic. The finite strain pattern of refolded folds results from the superimposition of at least two late Neoproterozoic deformation events characterized by early sub-horizontal foliations and a later network of kilometer-scale vertical shear zones bounding intensely folded domains. These latest upright shears are clearly related to late Neoproterozoic horizontal shortening in a transpressive regime under granulite facies conditions.

The western third of Madagascar is covered by Upper Carboniferous (300 million years old) to mid-Jurassic (180 million years old) basinal deposits that are equivalents to the Karoo and other Gondwanan sequences of Africa and India. From south to north, these include the Morondova, Majunga (or Mahajanga), and Diego (or Ambilobe) basins. Each has a similar three-fold stratigraphic division including the Sakoa, Sakamena, and Isalo Groups consisting of mainly sandstones, limestones, and basalts, overlain by unconsolidated sands in the south and along the western coast. These basins formed during rifting of Madagascar from Africa, and have conjugate margins along the east coast of southern and central Africa. The base of the Morondova basin, the oldest of the three, has spectacular glacial deposits including diamictites, tillites, and glacial outwash gravels. These are overlain by coals and arkoses, along with plant fossil (Glossopteris) rich mudstones thought to represent meandering stream deposits. Marine limestones cap the Sakoa Group. Fossiliferous deltaic and lake deposits of the Sakamena group prograde (from the east) over the Sakoa Group. The uppermost Isalo Group is 0.6–3.7 miles (1–6 km) thick, consisting of large-scale cross-bedded sandstones, overlain by red beds and fluvial deposits reflecting arid conditions. Mid-Jurassic limestones (Ankara and Kelifely Formations) mark a change to subaqueous conditions throughout the region.

EXTENSION OF THE EAST AFRICAN RIFT TO MADAGASCAR AND THE INDIAN RIDGE

Madagascar rifted from Gondwana in two stages, starting its separation from the Somali coast of Africa some 160 million years ago, and following up with a break from India and the Seychelles between 90 and 66 million years ago. The island has been tectonically isolated as an island in the Indian Ocean since the end of the Cretaceous.

The Davie Ridge runs north northwest through the Mozambique Channel to the west of Madagascar, and represents the now presumed-extinct transform along which Madagascar separated from Somalia between 160 and 117 Ma ago. Parts of the Davie Ridge are close to parallel with a prominent valley, the Alaotra-Ankay rift, that cuts the central plateau of Madagascar. Dredge samples from the Mozambique channel show that isolated blocks of Precambrian basement are preserved along this paleo-transform and that the region has seen volcanism and deformation since Madagascar reached its present location with respect to Africa. These volcanics include both Late Cretaceous fields and Cenozoic (Eocene-Miocene) flows.

With this simple post-Gondwana tectonic history in mind, Madagascar should by all rights have subdued topography, no volcanism, no earthquakes, and be a quiescent isolated continental block separated by rifting, passively weathering away as it waits to be incorporated into a collisional orogen as an exotic terrane in the future. However, Madagascar is anything but a passive isolated continental block, behaving by slowly subsiding and eroding. The thick tropical soils have in many places passed a critical threshold and are collapsing into steep canyonlands called lavakas, and the island-continent is beveled in many places by distinct erosion surfaces that have as yet escaped a unifying explanation. Some of these could be old, but others cut Cenozoic and even Neogene rocks, so much of the uplift of the island has occurred in the past 10–15 million years, perhaps spawning the current accelerated erosion. Madagascar has active earthquakes, active volcanoes, hot springs, and high juvenile topography that reaches 1.7 miles (2.8 km) above sea level within 250 miles (400 km) of the coast.

Perhaps the most striking features of Madagascar's active tectonics are the eastern coast, a straight, fault-controlled coastline that extends for more than 750 miles (1,200 km) of the 1,000-mile- (1,600-km-) long coastline, the high central Ankaratra plateau, and the oblique Ankay-Alaotra rift striking north-south through the island.

The east coast of Madagascar exhibits a juvenile, stepped topography that follows a staircase up from the coast to an elevation of more than 1.25 miles (2 km) over a cross strike distance of only 250 miles (400 km) at 22 degrees south latitude. Crustal extension and rotation of flat-topped fault blocks is demarcated by the juvenile topography along the southeast coast, and in the Ankay-Alaotra rift, similar in many ways to topography along the Gulf of Aqaba where Arabia is sliding north relative to Sinai.

At a slight angle to the coast is the Ankay-Alaotra rift, where topography falls 0.3–0.44 miles (0.5–0.7 km) across stepped fault scarps over a distance of several miles. Studies indicate tectonic activity in the Late Cretaceous, but indexes of active tectonics indicate active subsidence and relative uplift of rift shoulders as confirmed by the active seismicity, active volcanism, and the wonderfully warm hot springs of the high plateau.

Madagascar experiences thousands of earthquakes with magnitudes between 2.9–6.0 each year, and these earthquakes delineate several prominent areas of activity and northwest trends that parallel late structures on the surface. The most active area is beneath the Ankaratra plateau, where thousands of earthquakes occur annually at depths of 9–17 miles (15–28 km) and have included magnitude 5.2 and 5.5 events in 1985 and 1991. The rift valley of Lake Alaotra-Ankay graben is also seismically active, and the earthquakes show both a concentration parallel to the north-south strike of the rift, and a secondary northwest trend parallel to the swarm extending from the Ankaratra volcanic field.

Neogene to Quaternary volcanic rocks and active hot springs are found in several locations on the high central plateau of Madagascar. The Ankaratra volcanics form extensive flows and volcanic cones of basalt, basanite, and phonolite cover the Ankaratra plateau at elevations of 1.4–1.7 miles (2.3–2.7 km). Similar volcanics extend to the Itasy area to the northwest, and are found in the Neogene sediments of the Lake Alaotra rift basin. Ocean island basalts, basanites, and phonotephrites with ages of 7–10 Ma form prominent outcrops in the Ambohitra volcanic field of Nosy Be on the northern coast.

The volcanism on the northern coast of Madagascar is most likely related to young volcanism in the Comoros. Off the northwest corner of Madagascar a series of shallow marine platforms extends to the recently volcanically active Comoros Islands.

The Comoros consist of westward-younging volcanics that erupted through 55–60-mile- (~100-km-) thick, 135–142 Ma-old lithosphere. The similarity of the Comoros and Nosy Be volcanics suggests that they both formed either from migration of the Somali plate over a postulated Comoros hot spot, or northwest-propagation of rift-related faults from Madagascar formed deep faults that acted as conduits for the young magmas to reach the surface from the mantle. The progressive westward younging of the volcanics supports the hot-spot track model.

CRETACEOUS VOLCANICS AND THE MARION HOT SPOT

On the southern side of the island of Madagascar, the shallow-water Madagascar plateau extends 500 miles (800 km) south along the Marion hot spot track to Marion Island. The volcanics associated with this hot spot track correlate with the Late Cretaceous (90 Ma) volcanics abundant on the island, associated with the separation of Madagascar from the Seychelles and India. They become younger progressively to the south to zero-age volcanic on Marion Island. Madagascar was most likely flat and near sea level in the Late Cretaceous 90 million years ago, and may have been entirely covered by flood basalts from the large igneous province associated with the breakup of India, the Seychelles, and Madagascar. The flood basalts from different parts of the island had different sources, but still all formed between 92–84 Ma. In all of these cases, more than 80 million years has elapsed since Madagascar was influenced by the Marion plume. The active faulting, volcanism, and uplift are therefore not related to the passage of Madagascar over the Marion hot spot.

ACTIVE FAULTING OF LAKE ALAOTRA, CENTRAL MADAGASCAR

The Lake Alaotra-Ankay rift valley of central Madagascar forms a roughly northeast-southwest oriented depression that is filled with Neogene to Recent sediments, and is part of a more regional post-Miocene graben system that strikes north-south across much of the central part of the island. The region is characterized by a number of small earthquakes, steep fault-scarp bound valleys, several levels of terraces, and deeply incised topography related to intense tropical weathering. The origin and evolution of this extensional structure and its morphological expressions, however, are not clearly documented.

The rift valley is bordered by uplifted shoulders rising up to 0.4 miles (0.7 km) to the west and 0.3 miles (0.5 km) to the east. The biggest lake of the island, Lake Alaotra, is located adjacent to eastern termination of the Alaotra basin. The lake is 0.5 miles (0.75 km) above sea level with very shallow (average 16 feet or 5 meters) water level. It has lost 60 percent of its original size during the last 46 years due to deforestation-driven extreme erosion, and thus most of the modern basin is covered with recent alluvia, swamps, and rice fields. The eastern branch is morphologically more distinct in the field and in remotely sensed images, with several segments striking N-N35E with west-dipping fault planes, creating a series of escarpments up to 500 feet (150 m) high with well-developed triangular facets and short and steep fault scarp–bounded valleys. Terraces form prominent surfaces at several levels that correspond to successive stages in the local base level; higher, east-tilted surfaces between the highest and lowest surfaces correspond to fault displacements of a single surface. A number of faults cut basement units, forming fault zones and debris flow fans in intermountain domains of the eastern side of Lake Alaotra. These faults are mostly parallel to the structural fabric of basement rocks and form stair-step morphology. The western side of the Alaotra Basin is limited by north northeast-striking, east-dipping sub-parallel fault zones with less pronounced morphological signature.

The topographic gradient between the rift basin and shoulders is much steeper in the Ankay Basin, which is ~57 miles (92 km) long and ~20 miles (32 km) wide and bounded by a single west-dipping fault segment on the east and several east-dipping fault systems on the west. The western termination of the Ankay basin morphologically forms ~0.3-mile- (0.5-km-) high escarpments in some places. Although the border faults strike approximately north-south, they are cut by a set of northeast-southwest-striking faults. The Alaotra and Ankay basins are separated by a topographically high region, Andaingo Heights, which has dissected morphology by normal faulting but without any prominent basin fills.

POSSIBLE TECTONIC TRIGGERS OF THE ACTIVE TECTONICS OF MADAGASCAR

Several phenomena could potentially induce the active tectonic features of Madagascar described above. Passage of Madagascar and the Somali plate over a postulated Comoros hot spot is one mechanism that can explain the young volcanics and topography in northernmost Madagascar and in the Comoros, but it does not adequately explain the young topography in the center of the island, nor the active faulting in the Ankay-Alaotra rift, nor the straight eastern coastline.

Extension in the Ankay-Alaotra rift is oriented roughly the same as in the morphologically similar East African rift system, located only 300 miles (500 km) to the west. The eastern edge of the African continent is moving somewhat independently from the rest of Africa and the portion of the African plate east of the East African rift is regarded as a separate plate, the Somali plate. However, few if any plate configurations have clearly defined the southern extension of the Africa-Somali plate to where it must join the Southwest Indian Ocean ridge in order to be a true microplate bounded by plate boundaries. The plate boundary probably extends off the coast of Africa through the Comoros, then cuts through northern Madagascar and extends down the active Ankay-Alaotra rift to the fault-block dominated southeastern coast of Madagascar, then extends southeastward to the Southwest Indian Ocean ridge. If this suggestion is confirmed, then the southeastern part of the African plate is considerably fragmented by plume-related uplift and extensional events.

See also AFRICAN GEOLOGY; DIVERGENT PLATE MARGIN PROCESSES; ECONOMIC GEOLOGY; EROSION; GREENSTONE BELTS; OROGENY; PRECAMBRIAN; PROTEROZOIC.

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magma Molten rock beneath the surface of the Earth is known as magma. When magma reaches the surface, it is known as lava, which may flow or explosively erupt from volcanoes. The wide variety of eruption styles and hazards associated with volcanoes around the world can be linked to variations in several factors, including different types of magma, different types of gases in the magma, different volumes of magma, different forces of eruption, and different areas that are affected by each eruption. Different types of magma form in distinct tectonic settings, explaining many of the differences above. Other distinctions between eruption styles are explained by the variations in processes that occur in the magma as it makes its way from deep within the Earth to the surface at a volcanic vent.

Most magma solidifies below the surface, forming igneous rocks (*igneous* is from the Latin word for fire). Igneous rocks that form below the surface are called intrusive or plutonic rocks, whereas those that crystallize on the surface are called extrusive or volcanic rocks. Rocks that crystallize at a very shallow depth are called hypabyssal rocks. Some common plutonic rock types include granites, and some of the most abundant volcanic rocks include basalts and rhyolites. Intrusive igneous rocks crystallize slowly, giving crystals an extended time to grow, thus forming rocks with large mineral grains that are clearly distinguishable with the naked eye. These rocks are called phanerites. In contrast, magma that cools rapidly forms fine-grained rocks. Aphanites are igneous rocks in which the component grains can not be distinguished readily without a microscope and are formed when magma from a volcano falls or flows across the surface and cools quickly. Some igneous rocks, known as porphyries, have two distinct populations of grain size. One group of very large crystals (called phenocrysts) is mixed with a uniform groundmass or matrix filling the space between the large crystals. This indicates two stages of cooling, as when magma has resided for a long time beneath a volcano, growing big crystals. When the volcano erupts it spews out a mixture of the large crystals and liquid magma that then cools quickly, forming the phenocrysts and the fine-grained groundmass.

MAGMA COMPOSITION AND NAMING IGNEOUS ROCKS

Determining whether an igneous rock is phaneritic or aphanitic is just the first stage in giving it a name. The second stage is determining its chemical com-

Fountaining and lava flow from Pu'u O eruption of Kilauea, Hawaii, January 31, 1984 *(J.D. Griggs, USGS)* ponents. The composition of magma is controlled by the most abundant elements in the Earth, including silicon (Si), aluminum (Al), iron (Fe), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), hydrogen (H), and oxygen (O). Oxygen is the most abundant ion in the crust of the Earth, so petrologists usually express compositional variations of magmas in terms of oxides. For most magmas the largest constituent is represented by the combination of one silicon atom with two oxygen atoms, forming silicon dioxide, more commonly called silica. Three very narrow compositional variations in the silica content of magma are common. The first type has about 50 percent silica (SiO_2), the second 60 percent, and the third 70 percent. These volcanic rock types are called basalt, andesite, and rhyolite, and the corresponding plutonic rocks gabbro, diorite, and granite. The table "Classification of Igneous Rocks" discusses the different kinds of igneous rocks. Some of the variation in the nature of different types of volcanic eruptions can be understood by examining what causes magmas to have such a wide range in composition.

EXTRUSIVE IGNEOUS ROCKS

Magma that reaches the Earth's surface and flows as hot streams or is explosively blown out of a volcano is called lava. Lava has a range of compositions, a variety of high temperatures, and flows at various speeds.

The chemical composition of magma closely relates to how explosive and hazardous a volcanic eruption will be. The variation in the amount of silica (SiO_2) in igneous rocks is used to describe the variation in composition of igneous rocks—and the magmas that formed them. Rocks with low amounts of silica (basalt, gabbro) are known as mafic rocks, whereas rocks with high concentrations of silica (rhyolite, granite) are known as silicic or felsic rocks.

All magmas have a small amount of gas dissolved in them, usually comprising between 0.2–3 percent of the magma volume, and this is typically water vapor and carbon dioxide. The gases typically control such features as how explosive a volcanic eruption can be with greater abundances of gases leading to more explosive eruptions.

Magmas exhibit a wide range in temperatures. Measuring the temperature of an erupting volcano is difficult, since temperatures typically exceed 930°F (500°C) and melt most thermometers. Also, the volcano may explode, killing the people who try to measure its temperature. Therefore, temperature is measured from a distance using optical devices, yielding temperatures in the range of 1,900–2,200°F (1,040–1,200°C) for basaltic magma, and as low as 1,155°F (625°C) for some rhyolitic magmas.

Magmas can move downhill at very variable rates. For example, in Hawaii magma often flows downhill in magma streams at about 10 miles per hour (16 km/hr), destroying whole neighborhoods, whereas in other places it may move downhill so slowly as to be hardly detectable. At the other end of the spectrum some explosive volcanic ash clouds move downhill at speeds of several hundred miles (km) per hour, destroying all in their path. The measure of the resistance to flow of magma is called viscosity. The more viscous a magma, the less fluid it is. Honey is more viscous than water. The viscosity of magma depends on its temperature and composition. Higher-temperature magma such as basalt tends to have a higher fluidity (lower viscosity) than lower temperature magma such as rhyolite, explaining why basaltic flows tend to move over large distances, whereas rhyolitic magmas form large steep sided domes around the volcanic vent they erupted from. Magmas with more silica in them (like rhyolite) are more resistant to flow because the silica molecule forms bonds with other atoms (mostly oxygen), forming large chains and rings of molecules that offer more resistance to flow than magmas without these large interlocking molecules.

INTRUSIVE IGNEOUS BODIES

Once magmas are formed from melting rocks deep within the Earth, they rise to intrude the crust and may take several forms. A pluton is a general name for a large cooled igneous intrusive body in the Earth. The name of the specific type of pluton is based on its geometry, size, and relations to the older rocks surrounding the pluton, known as country rock. Concordant plutons have boundaries parallel to layering

CLASSIFICATION OF IGNEOUS ROCKS

Magma Types	% SIO_2	Volcanic Rock	Plutonic Rock
mafic	45–52%	basalt	gabbro
intermediate	53–65%	andesite	diorite
felsic	>65%	rhyolite	granite

in the country rock, whereas discordant plutons have boundaries that cut across layering in the country rock. Dikes are tabular but discordant intrusions, and sills are tabular and concordant intrusive rocks. Volcanic necks are conduits connecting a volcano with its underlying magma chamber. A famous example of a volcanic neck is Devils Tower in Wyoming. Some plutons are so large that they have special names. Batholiths have a surface area of more than 60 square miles (100 km^2).

Batholiths contain hundreds to thousands of cubic miles of formerly molten magma, being more than 39 square miles (100 km^2) on the surface and typically extending many miles deep. Scientists have long speculated on how such large volumes of magma intrude the crust and what relationships these magmas have to the style of volcanic eruption. One mechanism that may operate is assimilation, where the hot magma melts surrounding country rocks as it rises, causing it to become part of the magma. In doing this, the magma becomes cooler, and its composition changes to reflect the added melted country rock. Most geologists think that magmas may rise only a very limited distance by the process of assimilation. Some magmas may forcefully push their way into the crust if there are high pressures in the magma. One variation of this forceful emplacement style is diapirism, where the weight of surrounding rocks pushes down on the melt layer, which squeezes its way up through cracks that can expand and extend, forming volcanic vents at the surface. Stoping is a mechanism of igneous intrusion whereby big blocks of country rock above a magma body get thermally shattered, drop off the top of the magma chamber, and fall into the chamber, much like a glass ceiling breaking and falling into the space below; the magma then moves upward to take the place of the sunken blocks.

THE ORIGIN OF MAGMA

Magmas come from deep within the Earth. The processes of magma formation at depth and its movement to the surface have been the focus of research for hundreds of years. The temperature generally increases with depth in the Earth, since the surface is cool and the interior is hot. The geothermal gradient is a measure of how temperature increases with depth in the Earth, and it provides information about the depths at which melting occurs and the depths at which magmas form. The differences in the composition of the oceanic and continental crusts lead to differing abilities to conduct the heat from the interior of the Earth, and thus different geothermal gradients. The geothermal gradients show that temperatures within the Earth quickly exceed 1,830°F (1,000°C) with depth, so why are these rocks not molten? The answer is that pressures are very high, and pressure influences the ability of a rock to melt. As the pressure rises, the temperature at which the rock melts also rises. However, this effect of pressure on melting is modified greatly by the presence of water, because wet minerals melt at lower temperatures than dry minerals. As the pressure rises, the amount of water that can be dissolved in a melt also increases. Therefore, increasing the pressure on a wet mineral has the opposite effect from increasing the pressure on a dry mineral—it decreases the melting temperature.

If a rock melts completely, the magma has the same composition as the rock. Rocks are made of many different minerals, all of which melt at different temperatures. Therefore, if a rock is slowly heated, the resulting melt or magma will first have the composition of the first mineral that melts. If the rock melts further, the melt will have the composition of the first plus the second minerals that melt, and so on. If the rock continues to completely melt, the magma will eventually end up with the same composition as the starting rock, but this does not always happen. What often occurs is that the rock only partially melts, so that the minerals with low melting temperatures contribute to the magma, whereas the minerals with high melting temperatures did not melt and are left as a residue (called a restite). In this way, the end magma can have a composition different from the rock it came from.

The phrase *magmatic differentiation by partial melting* refers to the process of forming magmas with differing compositions through the incomplete melting of rocks. For magmas formed in this way, the composition of the magma depends on both the composition of the parent rock and the percentage of melt.

BASALTIC MAGMA

Partial melting in the mantle leads to the production of basaltic magma, which forms most of the oceanic crust. By looking at the mineralogy of the oceanic crust, which is dominated by the minerals olivine (Mg_2SiO_4), pyroxene ($Mg,FeSi_2O_6$), and feldspar ($KAlSi_3O_8$), it is concluded that very little water is involved in the production of the oceanic crust. These minerals are all anhydrous, that is without water in their structure. Therefore partial melting of the upper mantle without the presence of water must lead to the formation of oceanic crust. By collecting samples of the mantle that have been erupted through volcanoes, geologists have determined that it has a composition of garnet peridotite (olivine + garnet + orthopyroxene). Experiments taking samples of this back to the laboratory and raising their temperature and pressure so that they reach the equivalent of the conditions at 60 miles (100 km) depth show that

10 percent to 15 percent partial melt of this garnet peridotite yields a basaltic magma.

Magma that forms at 60 miles (100 km) depth is less dense than the surrounding solid rock, so it rises, sometimes quite rapidly (at rates of half a mile [.8 km] per day measured by earthquakes under Hawaii). In fact, it may rise so fast that it does not cool off appreciably, erupting at the surface at more than 1,830°F (1,000°C). That is where basaltic magma comes from.

GRANITIC MAGMA

Granitic magmas are very different from basaltic magmas. They have about 20 percent more silica, and the minerals in granite include quartz (SiO_2) and the complex minerals mica $(K,Na,Ca)(Mg,Fe,Al)_2 AlSi_4 O_{10} (OH,F)_2$ and amphibole $((Mg,Fe,Ca)_2 (Mg,Fe,Al)_5 (Si,Al)_8 O_{22}(OH)_2)$, which both have a lot of water in their crystal structures. Also, granitic magmas are found almost exclusively in regions of continental crust. From these observations it is inferred that the source of granitic magmas is within the continental crust. Laboratory experiments suggest that when rocks with the composition of continental crust start to melt at temperature and pressure conditions found in the lower crust, a granitic liquid is formed, with 30 percent partial melting. These rocks can begin to melt either by the addition of a heat source, such as basalt intruding the lower continental crust, or by burying water-bearing minerals and rocks to these depths.

These granitic magmas rise slowly because of their high SiO_2 content and high viscosities until they reach the level in the crust where the temperature and pressure conditions are consistent with freezing or solidification of magma with this composition. This is about 3–6 miles (5–10 km) beneath the surface, which explains why large portions of the continental crust are not molten lava lakes. There are many regions with crust above large magma bodies (called batholiths) that are heated by the cooling magma. An example is Yellowstone National Park, where there are hot springs, geysers, and many features indicating that there is a large hot magma body at depth. Much of Yellowstone Park is a giant valley called a caldera, formed when an ancient volcanic eruption emptied an older batholith of its magma, and the overlying crust collapsed into the empty hole formed by the eruption.

ANDESITIC MAGMA

The average composition of the continental crust is andesitic, or somewhere between the composition of basalt and rhyolite. Laboratory experiments show that partial melting of wet oceanic crust yields an andesitic magma. Most andesites today are erupted along continental margin convergent boundaries where a slab of oceanic crust is subducted beneath the continent. Remember that oceanic crust is dry, but after it forms it interacts with seawater, which fills cracks to several miles (kilometers) depth. Also, the sediments on top of the oceanic crust are full of water, but these are for the most part nonsubductable. Andesite forms above places where water is released from the subducted slabs, and it migrates up into the mantle wedge above the subducting slab, forming water-rich magmas. These magmas then intrude the continental crust above, some forming volcanic andesites, others crystallizing as plutons of diorite at depth.

SOLIDIFICATION OF MAGMA

Just as rocks partially melt to form different liquid compositions, magmas may solidify to different minerals at different times to form different solids (rocks). This process also results in the continuous change in the composition of the magma—if one mineral is removed the resulting composition is different. If this occurs, a new magma composition results.

The removal of crystals from the melt system may occur by several processes, including the squeezing of melt away from the crystals or by the sinking of dense crystals to the bottom of a magma chamber. These processes lead to magmatic differentiation by fractional crystallization, as first described by Norman Levi Bowen. Bowen systematically documented how crystallization of the first minerals changes the composition of the magma, and results in the formation of progressively more silicic rocks with decreasing temperature.

See also CONTINENTAL CRUST; CONVERGENT PLATE MARGIN PROCESSES; DIVERGENT PLATE MARGIN PROCESSES; PETROLOGY AND PETROGRAPHY; VOLCANO.

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magnetic field, magnetosphere The Earth has a magnetic field that is generated within the core of the planet. The field is generally approximated as a dipole, with north and south poles, and magnetic field lines that emerge from the Earth at the magnetic south pole, and reenter at the magnetic north pole. The field is characterized at each place on the planet by an inclination and a declination. The inclination is a measure of how steeply inclined the field lines are with respect to the surface, with low inclinations near the equator, and steep inclinations near the poles. The declination measures the apparent angle between the rotational North Pole and the magnetic north pole.

The Earth's magnetic field orientation is commonly traced using a magnetic compass, an instrument that indicates the whole circle bearing from the magnetic meridian to a particular line of sight. It consists of a needle that aligns itself with the Earth's magnetic flux and with some type of index that allows for a numeric value for the calculation of bearing. A compass can be used for many things. The most common application is for navigation. People are able to navigate throughout the world by simply using a compass and map. The accuracy of a compass is dependent on other local magnetic influences such as man-made objects or natural abnormalities such as local geology. The compass needle does not really point true north, but is attracted and oriented by magnetic force lines that vary in different parts of the world and that are constantly changing. For example, north on a compass shows the direction toward the magnetic north pole. To offset this phenomenon a declination value is used to convert the compass reading to a usable map reading. Since the magnetic flux changes through time it is necessary to replace older maps with newer maps to insure accurate and precise up-to-date declination values.

The magnetic field originates in the liquid outer core of the Earth and is thought to result from electrical currents generated by convective motions of the iron-nickel alloy from which the outer core is made. The formation of the magnetic field by motion of the outer core is known as the geodynamo theory, pioneered by Walter M. Elsasser of Johns Hopkins University in the 1940s. The basic principle for the generation of the field is that the dynamo converts mechanical energy from the motion of the liquid outer core, which is an electrical conductor, into electromagnetic energy of the magnetic field. The convective motion of the outer core, maintained by thermal and gravitational forces, is necessary to maintain the field. If the convection stopped or if the outer core solidified, generation of the magnetic field would cease. Secular variations in the magnetic field have been well-documented by examination of the paleomagnetic record in the seafloor, lava flows, and sediments. Every few thousand years the magnetic field changes intensity and reverses, with the north and south poles abruptly flipping.

Studies of the record of ancient magnetism in rocks, called paleomagnetism, have revealed that the Earth's magnetic poles can flip suddenly, over a period of thousands or even hundreds of years. The magnetic poles also wander by about 10–20° around the rotational poles. On average, however, the magnetic poles coincide with the Earth's rotational poles. A researcher can use this coincidence to estimate the north-south directionality in ancient rocks that have drifted or rotated in response to plate tectonics. Determination of the natural remnant magnetism in rock samples can, under special circumstances, reveal the paleoinclination and paleodeclination, which can be used to estimate the direction and distance to the pole at the time the rock acquired the magnetism. If these parameters can be determined for a number of rocks of different ages on a tectonic plate, then an apparent polar wander path for that plate can be constructed. These show how the magnetic pole has apparently wandered with respect to (artificially) holding the plate fixed—when the reference frame is switched, and the pole is held fixed, the apparent polar wander curve shows how the plate has drifted on the spherical Earth.

MAGNETOSPHERE

The magnetosphere encompasses the limits of the Earth's magnetic field, as confined by the interaction of the solar wind with the planet's internal magnetic field. The natural undisturbed state of the Earth's magnetic field is broadly similar to a bar magnet, with magnetic flux lines (of equal magnetic intensity and direction) coming out of the south polar region, and returning back into the north magnetic pole. The solar wind, consisting of supersonic H^+ and $^4He^{2+}$ ions expanding away from the Sun, deforms this ideal state into a teardrop-shaped configuration known as the magnetosphere. The magnetosphere has a rounded compressed side with about 6–10 Earth radii facing the sun, and a long tail (magnetotail) on the opposite side that stretches past the orbit of the moon. The magnetotail is probably open, meaning that the magnetic flux lines never close but instead merge with the interplanetary magnetic field. The magnetosphere shields the Earth from many of the charged particles from the Sun by deflecting them around the edge of the magnetosphere, causing them to flow harmlessly into the outer solar system.

The Sun periodically experiences periods of high activity when many solar flares and sunspots form. During these periods the intensity of the solar wind emissions increases, and the solar plasma is emitted with greater velocity, in greater density, and with more energy than in its normal state. As a result of the high solar activity, the extra pressure of the solar wind distorts the magnetosphere and causes it to move around, also causing increased auroral activity.

See also AURORA, AURORA BOREALIS, AURORA AUSTRALIS; GEODYNAMICS; GEOPHYSICS.

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Stern, David P., and Mauricio Peredo. *The Exploration of the Earth's Magnetosphere.* Available online. URL: http://www-istp.gsfc.nasa.gov/Education/Intro.html. Last updated November 20, 2003.

mantle The mantle forms about 80 percent of the Earth by volume, occupying the region between the crust and upper core, between about 22 and 1,802 miles (35–2,900 km) in depth. Divided into two regions, the upper and lower mantle, the crust is composed predominantly of silicate minerals in closely packed high-pressure crystal structures. Some of these are high-pressure forms of more common silicates, formed under high temperature and pressure conditions found in the deep Earth. The upper mantle extends to a depth of about 416 miles (670 km), and the lower mantle extends from there to the core-mantle boundary near 1,802 miles (2,900 km) depth.

Most knowledge about the mantle comes from seismological and experimental data as well as from rare samples of upper mantle material that has made its way to the surface in kimberlite pipes, volcanoes, and in some ophiolites and some other exhumed subcrustal rocks. Most of the mantle rock samples that have made their way to the surface are composed of peridotite, with a mixture of the minerals olivine, pyroxene, and some garnet. The velocities of seismic waves depend on the physical properties of the rocks through which they travel. Seismic experiments show that S-waves (shear waves) propagate through the mantle, and since S-waves do not propagate through liquids, the mantle must be a solid rocky layer. The temperature does not increase dramatically from the top to the bottom of the mantle, indicating that an effective heat transfer mechanism is operating in this region. Heat transfer by convection, in which the material of the mantle is flowing in large-scale rotating cells, is a very efficient mechanism that effectively keeps this region at nearly the same temperature throughout. In contrast, the lithosphere (occupying the top of the mantle and crust) cools by conduction rather than convection, so it shows a dramatic temperature increase from top to bottom.

There are several discontinuities in the mantle, where seismic velocities change across a discrete layer or zone. Between about 62 and 155 miles (100–250 km) depth, both P- and S-waves (compressional and shear waves) decrease in velocity, indicating that this zone probably contains a few percent partial melt. This low velocity zone is equated with the upper part of the asthenosphere, upon which the plates of the lithosphere move. The low velocity zone extends around most of the planet; however, it has not been detected beneath many Archean cratons that have thick roots, leading to uncertainty about the role that the low velocity zone plays in allowing these cratons to move with the tectonic plates. The asthenosphere extends to about 416–435 miles (670–700 km) depth. At 250 miles (400 km), an abrupt increase in seismic velocities occurs, associated with an isochemical phase change of the mineral olivine ($(Mg,Fe)_2SiO_4$) to a high-pressure mineral known as wadsleyite (or betaphase), and then at 323 miles (520 km) this converts to a high-pressure spinel known as ringwoodite. The base of the asthenosphere at 416 miles (670 km) is also associated with a phase change from spinel to the minerals perovskite ($(Mg,Fe)SiO_3$) and magnesiowüstite ($(Mg,Fe)O$), stable through the lower mantle or mesosphere that extends to 1,802 miles (2,900 km).

The nature of the seismic discontinuities in the mantle has been debated for decades. Professor Alfred E. "Ted" Ringwood, an Australian petrologist, proposed a model in which the composition of the mantle started off essentially homogeneous, consisting of the hypothetical composition pyrolite (82 percent harzburgite and 18 percent basalt). Extraction of basalt from the upper mantle has led to its depletion relative to the lower mantle. An alternative model, proposed by Professor Don Anderson from California Institute of Technology, poses that the mantle is compositionally layered, with the 415-mile (670-km) discontinuity representing a chemical as well as a phase boundary, with more silica-rich rocks at depth. As such, this second model requires that convection in the mantle be of a two-layer type, with little or no mixing between the upper and lower mantle to maintain the integrity of the chemical boundary. Recent variations on these themes include a two-layered convecting mantle with subducting slab penetration downward through the 415-mile (670-km) discontinuity, and mantle plumes that move up from the core mantle boundary through the 415-mile (670-km) discontinuity. In this model, the unusual region at the base of the mantle known as D″ (dee-double-prime) may be a place where many subducted slabs have accumulated.

The unusual basal D″ region of the mantle represents one of the most significant boundaries in the Earth. The viscosity contrast across the boundary is huge, being several times that of the rock/air interface. D″ is a boundary layer, so temperatures increase rapidly through the layer, and a huge seismic discontinuity exists at the boundary. P-waves drop in velocity from about 8.5 to 4 miles per second (14 to 8 km/s), and S-waves do not propagate across the boundary since the outer core is a liquid. Research into the nature of the D″ layer is active, and several ideas have emerged as possibilities for the nature of this region: the D″ layer could be a slab graveyard, where subducted slabs temporarily accumulate; a chemical reaction zone between the lower mantle and outer core; a remnant of chemical layering formed during the early accretion and differentiation of the Earth; or material that crystallized from the core and floated to accumulate at the core/mantle boundary. Whatever the case, an analog to plate tectonics may operate in this region, since it is a viscosity and thermal boundary layer subjected to basal traction forces by the rapidly convecting outer core.

See also CONVECTION AND THE EARTH'S MANTLE; ENERGY IN THE EARTH SYSTEM; LITHOSPHERE; MANTLE PLUMES; PLATE TECTONICS.

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mantle plumes

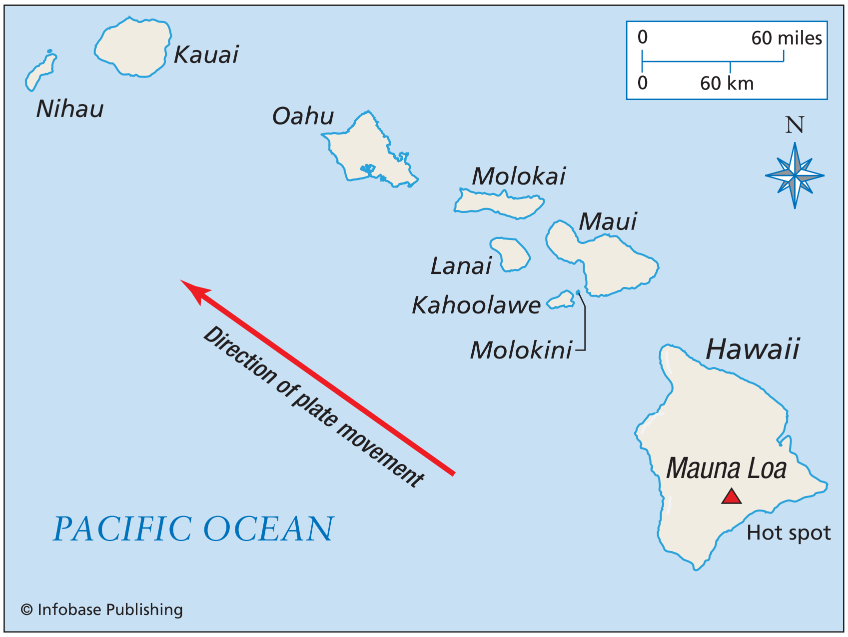
The mantle of the Earth convects with large cells that generally upwell beneath the oceanic ridges and downwell with subduction zones. These convection cells are the main way that the mantle loses heat. In addition to these large cells, a number of linear plumes of hot material upwell from deep within the mantle, perhaps even from the core-mantle boundary. Heat and material in these plumes move at high velocities relative to the main mantle convection cells, and therefore burn their way through the moving mantle and reach the surface, forming thick sequences of generally basaltic lava. These lavas are chemically distinct from mid-ocean ridge and island arc basalts, and they form either as continental flood basalts, oceanic flood basalts (on oceanic plateaus), or shield volcanoes.

Mantle plumes are postulated to be upper mantle hot spots that were relatively stationary with respect to the moving plates, because a number of long linear chains of islands in the oceans were found to be parallel, and all old at one end and younger at the other end. In the 1960s when plate tectonics was first recognized, it was suggested that these hot spot tracks were formed when the plates moved over hot, partially molten spots in the upper mantle that burned their way, like a blow torch, through the lithosphere, and erupted basalts at the surface. As the plates moved, the hot spots remained stationary, so the plates had a series or chain of volcanic centers erupted through them, with the youngest volcano sitting above the active hot spot. The Hawaiian-Emperor island chain is one of the most exemplary of these hot spot tracks. Located in the north-central Pacific to the Pacific northwest near the Aleutian arc, the Hawaiian-Emperor island chain, which is about 70 million years old, shows a sharp bend in the middle of the chain where the volcanoes are 43 million years old, and then are progressively younger toward the island of Hawaii. Magmas beneath Hawaii are still molten, and are assigned an age of zero. The bend in the chain indicates a change in the plate motion direction and is reflected in a similar change in direction of many other hot spot tracks in the Pacific Ocean.

Geochemical data and seismic tomography has shown that the hot spots are produced by plumes of deep mantle material that probably rise from the D″ layer at the core-mantle boundary. These plumes may rise as a mechanism to release heat from the core or as a response to greater heat loss than is accommodated by convection. If heat is transferred from the core to D″, parts of this layer may become heated, become more buoyant, and rise as thin narrow plumes that rise buoyantly through the mantle. As they approach the base of the lithosphere the plumes expand outward, forming a mushroomlike plume head that may expand to more than 600 miles (1,000 km) in diameter. Flood basalts may rise from these plume heads, and large areas of uplift, doming, and volcanism may be located above many plume heads.

Geologists believe plumes exist beneath the African plate, such as beneath the Afar region, which has experienced uplift, rifting, and flood basalt volcanism. This region exemplifies a process whereby several (typically three) rifts propagate off a dome formed above a plume head, and several of these link up with rifts that propagated off other plumes formed over a large stationary plate. When several rifts link together, they can form a continental rift system that could become successful and expand into a young ocean basin, similar to the Red Sea. The linking of plume-related rifts has been suggested to be a mechanism to split supercontinents that have come to rest (in a geoid low) above a number of plumes. The heat from these plumes must eventually escape by burning through the lithosphere, forming linked rift systems that eventually rip apart the supercontinent.

Some areas of anomalous young volcanism may also be formed above mantle plume heads. For instance, the Yellowstone area has active volcanism and geothermal activity and is thought to rest above the Yellowstone hot spot, which has left a track extending northwest back across the flood basalts of the Snake River plain. Other flood basalt provinces probably formed in a similar way. For instance, the 65-million-year-old Deccan flood basalts of India formed when this region was over the Reunion hot spot that is presently in the Indian Ocean, and these may be related to a mantle plume.



Map of Hawaii-Emperor chain formed by a hot spot track as the Pacific plate moved over a mantle plume. The youngest volcanoes are found on the island of Hawaii (Mauna Loa), and they get progressively older toward the northwest.

Mantle plumes may also interact with mid-ocean ridge volcanism. For instance, the island of Iceland is located on the Reykjanes Ridge, part of the mid-Atlantic ridge system, but the height of the island is related to unusually thick oceanic crust produced in this region because a hot spot (plume) has risen directly beneath the ridge. Other examples of mantle plumes located directly beneath ridges are found in the South Atlantic Ocean, where the Walvis and Rio Grande Ridges both point back to an anomalously thick region on the present-day ridge where the plume head is located. As the South Atlantic opened, the thick crust produced at the ridge on the plume head split, half being accreted to the African plate, and half being accreted to the South American plate.

See also CONVECTION AND THE EARTH'S MANTLE; ENERGY IN THE EARTH SYSTEM; HOT SPOT; LARGE IGNEOUS PROVINCES, FLOOD BASALT; MANTLE.

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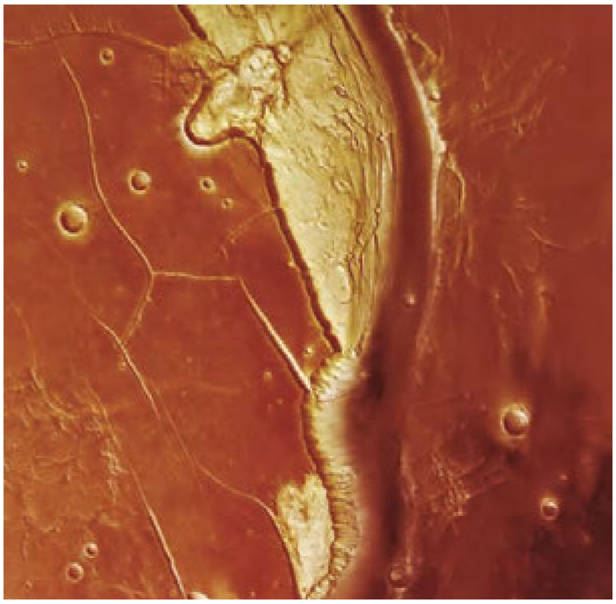
Mars The fourth planet from the Sun, Mars is only 11 percent of the mass of Earth and has an average density of 3.9 grams per cubic centimeter and a diameter of 4,222 miles (6,794 km). Mars orbits the Sun every 687 days at a distance of 142 million miles (228 million km) and has a period of rotation about its axis of 24 hours, 37 minutes, and 23 seconds.

When viewed from Earth, Mars shows several striking surface features, including bright polar caps that consist mostly of frozen carbon dioxide (dry ice) that change in size with the seasons, almost disappearing in the Martian summer. Some spectacular canyons are also visible, including the 2,485-mile (4,000-km) long Valles Marineris. This canyon probably formed as a giant crack or fracture on the surface of the expanding bulge in the Tharsis region. Running water may have later modified its surface. Mars is prone to strong surface winds that kick up a lot of dust and generate dust storms that occasionally obscure the surface for long periods of time, an observation that led early observers to suggest that the planet may host vegetation and other life-forms.



Northern main channel of Kasei Valles on Mars *(ESA/DLR/FU Berlin, G. Neukum)*

Mars shows evidence for widespread volcanism in its past—its surface is covered with basaltic volcanic rocks, flows, and cones and hosts several large shield volcanoes in the Tharsis and Elysium regions. The Tharsis region is a huge, North America–sized bulge on the planet that rises on average 6.2 miles (10 km) above the elevation of surrounding regions. These volcanoes are huge compared to shield volcanoes on Earth. The largest volcano, Olympus Mons, is 435 miles (700 km) across, and several others are 220 to 250 miles (350–400 km) across and rise 12.5 miles (20 km) over the surrounding terrain. The northern hemisphere of Mars is made of rolling volcanic plains, similar to lunar maria (the dark flat areas on the Moon, shown to be lava flows), but formed by much larger volcanic flows than on Earth or the Moon. In contrast, the southern hemisphere consists of heavily cratered highlands, with a mean elevation several kilometers higher than the volcanic plains to the north. Estimates put the average age of the highland plains at 4 billion years, whereas the age of most of the volcanic plains in the north may be 3 billion years, with some volcanoes as young as 1 billion years old.

Recent high-resolution images of the surface of Mars have strengthened earlier views that water once ran across the surface of the planet. Outflow channels and runoff channels are common. Runoff channels form extensive systems in the southern hemisphere and resemble dried-up river systems. Outflow channels, which are most common in equatorial regions, may have formed during a catastrophic flooding episode about 3 billion years ago in the early history of the planet. Flow rates are estimated to have been at least one hundred times that of the Amazon River. The current absence of any water or visible water ice on the surface suggests that much of this water is frozen beneath the surface in a permafrost layer, reflecting a severe global cooling since 4 billion years ago.

The atmospheric pressure on Mars is only 1/150th that of Earth, and carbon dioxide makes up most of the gas in the atmosphere, with a few percent nitrogen, argon, oxygen, and carbon monoxide and less than one-tenth of a percent water vapor. The temperature rises from about -244°F at 62 miles (-153°C or 120 K at 100 km) above the surface, to about -10°F (-23°C or 250 K) at the surface, with surface temperatures on average about -82°F (-63°C or 50 K) cooler than on Earth.

Many early speculations centered on the possibility of life on Mars and several spectacular claims of evidence for life have been later found to be invalid. To date, no evidence for life, either present or ancient, has been found on Mars. The National Aeronautic and Space Administration (NASA) launched twin robot geologists to Mars in June and July of 2003, and these Rovers have been exploring the Martian surface since 2004. They have mapped a wide variety of rocks and surface structures on the planet, and returned numerous analyses and photographs. Some of the most exciting show evidence for past running water on the Martian surface and evidence that some of the landforms were carved by running water.

See also EARTH; JUPITER; MERCURY; NEPTUNE; SATURN; SOLAR SYSTEM; URANUS; VENUS.

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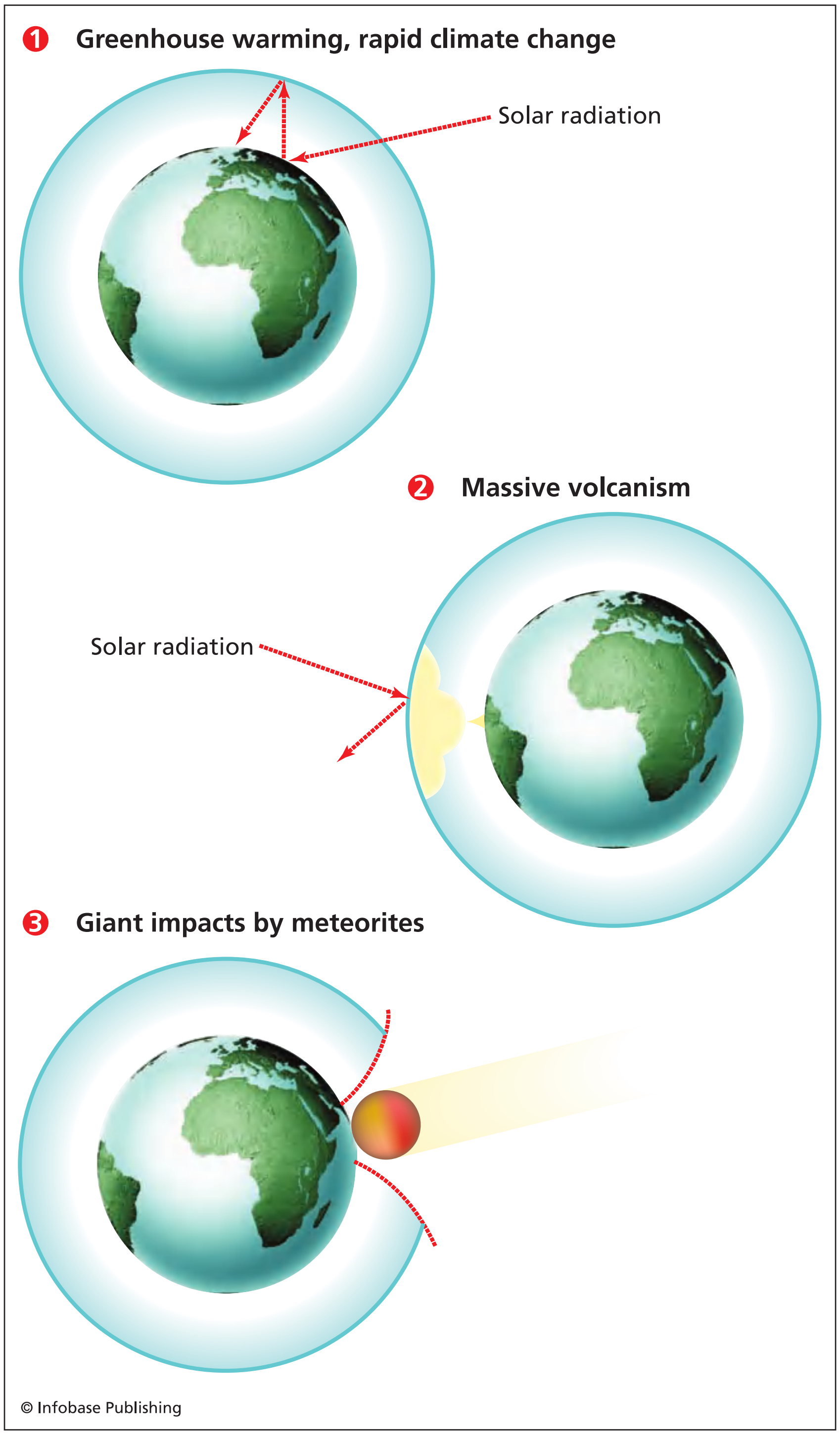
mass extinctions Geologists and paleontologists study the history of life on Earth through detailed examination of that record as preserved in sedimentary rock layers laid down one upon the other. For hundreds of years paleontologists have recognized that many organisms are found in a series of layers, and then suddenly disappear at a certain horizon never to reappear in the succeeding progressively younger layers. These disappearances have been interpreted to mark extinctions of the organisms from the biosphere. After hundreds of years of work, many of these rock layers have been dated by using radioactive decay dating techniques on volcanic rocks in the sequences, and many of these sedimentary rock sequences have been correlated with each other on a global scale. Some are associated with other deposits along the layers, indicating unusual concentrations of the metal iridium, carbon from massive fires, and other impact-related features such as tektites and tsunami deposits.

One of the more important findings resulting from such detailed studies is that the rock record preserves evidence of several extinction events that have occurred simultaneously on a global scale. Furthermore, these events do not just affect thousands or hundreds of thousand of members of a species, but they have wiped out many species and families each containing millions or billions of individuals.



The main causes for mass extinctions, including (1) greenhouse warming and rapid climate change, followed by (2) massive volcanism, and (3) giant impact from space objects such as asteroids or comets

PROCESSES THAT DRIVE EVOLUTION AND EXTINCTION

The progression of life-forms, evolution, and extinction can be influenced or driven by many factors including impacts with space objects such as meteorites and comets, variations in the style of plate tectonics or the positions of the continents, the supercontinent cycle, and continental collisions. Plate tectonics also may cause glaciation and climate changes, which in turn influence evolution and extinction.

One of the primary mechanisms by which plate tectonics drives evolution and extinction is through tectonic-induced changes to sea level. Fluctuating sea levels cause the global climate to fluctuate between warm periods when shallow seas are easily heated, and cold periods when glaciation draws the water down to place shorelines along the steep continental slopes. Many species cannot tolerate such variations in temperature and drastic changes to their shallow shelf environments, and thus become extinct. After organisms from a specific environment die off, their environmental niches are available for other species to inhabit.

Sea levels have risen and fallen dramatically in Earth history, with water covering all but 5 percent of the land surface at times, and water falling so that continents occupy 40 percent or more of the planet's surface at other times. The most important plate tectonic mechanism of changing sea level is to change the average depth of the seafloor by changing the volume of the mid-ocean ridge system. If the undersea ridges take up more space in the ocean basins, then the water will be displaced higher onto the land, much like dropping pebbles into a birdbath may cause it to overflow.

The volume of the mid-ocean ridge system can be changed through several mechanisms, all of which have the same effect. Young oceanic crust is hotter, more buoyant, and topographically higher than older crust. Thus, if the average age of the oceanic crust is decreased, then more of the crust will be at shallow depths, displacing more water onto the continents. If seafloor spreading rates are increased then the average age of oceanic crust will be decreased, the volume of the ridges will be increased, the average age of the seafloor will be decreased, and sea levels will rise. This has happened at several times in Earth history, including during the mid-Cretaceous between 110–85 Ma when sea levels were 660 feet (200 m) higher than they are today, covering much of the central United States and other low-lying continents with water. This also warmed global climates, because the Sun easily warmed the abundant shallow seas. It has also been suggested that sea levels were consistently much higher in the Precambrian, when seafloor spreading rates were likely to have been generally faster.

Sea levels can also rise from additional magmatism on the seafloor. If the Earth goes through a period when seafloor volcanoes erupt more magma on the seafloor, then the space occupied by these volcanic deposits will be displaced onto the continents. The additional volcanic rocks may be erupted at hot spot volcanoes like Hawaii or along the mid-ocean ridge system; either way, the result is the same.

A third way for the mid-ocean ridge volume to increase sea level height is to simply have more ridges on the seafloor. At the present time the mid-ocean ridge system is 40,000 miles (65,000 km) long. If the Earth goes through a period where it needs to lose more heat, such as in the Precambrian, one of the ways it may do this is by increasing the length of the ridge system where magmas erupt and lose heat to the seawater. Ridge lengths were probably greater in the Precambrian, which together with faster sea floor spreading and increased magmatism may have kept sea levels high for millions of years.

Glaciation that may be induced by tectonic or astronomical causes may also change sea level. At present glaciers cover much of Antarctica, Greenland, and mountain ranges in several regions. Approximately 6 million cubic miles (25,000,000 km^3) of ice is currently locked up in glaciers. If this ice were to all melt, then sea levels would rise by 230 feet (70 m), covering many coastal regions, cities, and interior farmland with shallow seas. During the last glacial maximum in the Pleistocene ice ages (20,000 years ago) sea levels were 460 feet (140 m) lower than today, with shorelines up to hundred of miles (km) seaward of their present locations, along the continental slopes.

Continental collisions and especially the formation of supercontinents can cause glaciations. When continents collide, many of the carbonate rocks deposited on continental shelves are exposed to weathering. As the carbonates and other minerals weather, the products react with atmospheric elements and tend to combine with atmospheric carbon dioxide (CO_2). Carbon dioxide is a greenhouse gas that keeps the climate warm, and steady reductions of CO_2 in the atmosphere by weathering or other processes lowers global temperatures. Thus, times of continental collision and supercontinent formation tend to be times that draw CO_2 out of the atmosphere, plunging the Earth into a cold "icehouse" period. In the cases of supercontinent formation, this icehouse may remain in effect until the supercontinent breaks up, and massive amounts of seafloor volcanism associated with new rifts and ridges add new CO_2 back into the atmosphere.

The formation and dispersal of supercontinent fragments, and migrating landmasses in general, also strongly influence evolution and extinction. When supercontinents break up, a large amount of shallow continental shelf area is created. Life-forms tend to flourish in the diverse environments on the continental shelves, and many spurts in evolution have occurred in the shallow shelf areas. In contrast, when continental areas are isolated, such as Australia and Madagascar today, life-forms evolve independently on these continents. If plate tectonics brings these isolated continents into contact, the different species will compete for similar food and environments, and typically only the strongest survive.

The position of continents relative to the spin axes (or poles) of the Earth can also influence climate, evolution, and extinction. At times (like the present) when a continent is sitting on one or both of the poles, these continents tend to accumulate snow and ice, and to become heavily glaciated. This causes ocean currents to become colder, lowers global sea levels, and reflects more of the Sun's radiation back to space. Together, these effects can put a large amount of stress on species, inducing or aiding extinction.

THE HISTORY OF LIFE AND MASS EXTINCTIONS

Life on Earth has evolved from simple prokaryotic organisms such as Archaea that appeared on Earth by 3.85 billion years ago. Life may have been here earlier, but the record is not preserved, and the method by which life first appeared is also unknown and the subject of much thought and research by scientists, philosophers, and religious scholars.

The ancient Archaea derived energy from breaking down chemical bonds of carbon dioxide, water, and nitrogen, and anaerobic archaeans have survived to this day in environments where they are not poisoned by oxygen. They presently live around hot vents around mid-ocean spreading centers, deep in the ground in pore spaces between soil and mineral grains, and in hot springs. The Archaea represent one of the three main branches of life; the other two branches are the Bacteria and the Eukarya. The plant and animal kingdoms are members of the domain Eukarya.

Prokaryotic bacteria (single-celled organisms lacking a cell nucleus) were involved in photosynthesis by 3.5 billion years ago, gradually transforming atmospheric carbon dioxide to oxygen and setting the stage for the evolution of simple eukaryotes (organisms containing a cell nucleus and membrane-bound organelles) in the Proterozoic. Two and half billion years later, by one billion years ago, cells began reproducing sexually. This long-awaited step allowed cells to exchange and share genetic material, speeding up evolutionary changes by orders of magnitude.

Oxygen continued to build in the atmosphere, and some of this oxygen was combined into ozone (O_3). Ozone forms a layer in the atmosphere that blocks ultraviolet rays of the Sun, forming an effective shield against this harmful radiation. When the ozone shield became thick enough to block a large portion of the ultraviolet radiation, life began to migrate out of the deep parts of the ocean and deep in land soils, into shallow water and places exposed to the Sun. Multicellular life evolved around 670 million years ago, around the same time that the supercontinent of Gondwana was forming near the equator. Most of the planet's landmasses were joined together for a short while, and then began splitting up and drifting apart again by 550 million years ago. This breakup of the supercontinent of Gondwana is associated with the most remarkable diversification of life in the history of the planet. In an incredibly short period of no longer than 40 million years, life developed complex forms with hard shells, and an incredible number of species appeared for the first time. This period of change marked the transition from the Precambrian era to the Cambrian period, marking the beginning of the Paleozoic era. The remarkable development of life in this period is known as the Cambrian explosion. In the past 540 million years since the Cambrian explosion, life has continued to diversify with many new species appearing.

The evolution of life-forms is also punctuated with the disappearance or extinction of many species, some as isolated cases, and others that die off at the same time as many other species in the rock record. A number of distinct horizons represent times when hundreds, thousands, and even more species suddenly died, being abundant in the record immediately before the formation of one rock layer and absent immediately above that layer. Mass extinctions are typically followed, after several million years, by the appearance of many new species and the expansion and evolution of old species that did not go extinct. These rapid changes are probably a response to availability of environmental niches vacated by the extinct organisms. The new species rapidly populate these available spaces.

Mass extinction events are thought to represent major environmental catastrophes on a global scale. In some cases these mass extinction events can be tied to specific likely causes, such as meteorite impact or massive volcanism, but in others their cause is unknown. Understanding the triggers of mass extinctions has important and obvious implications for ensuring the survival of the human race.

EXAMPLES OF MASS EXTINCTIONS

Most species are present on Earth for about 4 million years. Many species come and go during background level extinctions and evolution of new species from old, but the majority of changes occur during the distinct mass dyings and repopulation of the environment. The Earth's biosphere has experienced five major and numerous less significant mass extinctions in the past 500 million years (in the Phanerozoic era). These events occurred at the end of the Ordovician, in the Late Devonian, at the Permian-Triassic boundary, the Triassic-Jurassic boundary, and at the Cretaceous-Tertiary (K-T) boundary.

The early Paleozoic saw many new life-forms emerge in new environments for the first time. The Cambrian explosion led to the development of trilobites, brachiopods, conodonts, mollusks, echinoderms, and ostracods. Bryozoans, crinoids, and rugose corals joined the biosphere in the Ordovician, and reef-building stromatoporoids flourished in shallow seas. The end-Ordovician extinction is one of the greatest of all Phanerozoic time. About half of all species of brachiopods and bryozoans died off, and more than 100 other families of marine organisms disappeared forever.

The cause of the mass extinction at the end of the Ordovician appears to have been largely tectonic, as no meteorite impacts or massive volcanic outpourings are known from this time. The major landmass of Gondwana had been resting in equatorial regions for much of the Middle Ordovician, but migrated toward the South Pole at the end of the Ordovician. This caused global cooling and glaciation, lowering sea levels from the high stand they had been resting at for most of the Cambrian and Ordovician. The combination of cold climates with lower sea levels, leading to a loss of shallow shelf environments for habitation, probably was enough to cause the mass extinction at the end of the Ordovician.

The largest mass extinction in Earth history occurred at the Permian-Triassic boundary, over a period of about 5 million years. The Permian world included abundant corals, crinoids, bryozoans, and bivalves in the oceans, and on land, amphibians wandered about amid lush plant life. At the end of the Permian, 90 percent of oceanic species were to become extinct, and 70 percent of land vertebrates died off. This great catastrophe in Earth history did not have a single cause, but reflects the combination of various elements.

First, plate tectonics was again bringing many of the planet's land masses together in a supercontinent (this time, Pangaea), causing greater competition for fewer environmental niches by Permian life-forms. The rich continental shelf areas were drastically reduced. As the continents collided, mountains were pushed up, reducing the effective volume of the continents available to displace the sea, so sea levels fell, putting additional stress on life by further limiting the availability of favorable environmental niches. The global climate became dry and dusty, and the supercontinent formation led to widespread glaciation. This lowered the sea level even more, lowered global temperatures, and put many life-forms on the planet in a very uncomfortable position, and many of these went extinct.

In the final million years of the Permian, northern Siberia witnessed massive volcanic outpouring that dealt life a devastating blow. The Siberian flood basalts began erupting at 250 million years ago, becoming the largest known outpouring of continental flood basalts ever. Carbon dioxide was released in hitherto unknown abundance, warming the atmosphere and melting the glaciers. Other gases were also released, perhaps also including methane, as the basalts probably melted permafrost and vaporized thick accumulations of organic matter in high latitudes like that at which Siberia was located 250 million years ago.

The global biosphere collapsed, and evidence suggests that the final collapse happened in less than 200,000 years, and perhaps in less than 30,000 years. Entirely internal processes may have caused the end-Permian extinction, although some scientists now argue that an impact may have dealt the final death blow. For some time it was argued that the Manicouagan impact crater in Canada may be the crater from an impact that caused the Permian-Triassic extinction, but radiometric dating of the Manicouagan structure showed it to be millions of years too old to be related to the mass extinction. After the Permian-Triassic extinction was over, new life-forms populated the seas and land, and these Mesozoic organisms tended to be more mobile and adept than their Paleozoic counterparts. The great Permian extinction created opportunities for new life-forms to occupy now empty niches, and the most adaptable and efficient organisms took control. The toughest of the marine organisms survived, and a new class of land animals grew to new proportions and occupied the land and skies. The Mesozoic, time of the great dinosaurs, had begun.

The Triassic-Jurassic extinction is not as significant as the Permian-Triassic extinction. Mollusks were abundant in the Triassic shallow marine realm, with fewer brachiopods, and ammonoids recovered from near total extinction at the Permian-Triassic boundary. Sea urchins became abundant, and new groups of hexacorals replaced the rugose corals. Many land plants survived the end-Permian extinction, including the ferns and seed ferns that became abundant in the Jurassic. Small mammals that survived the end-Permian extinction rediversified in the Triassic, many only to become extinct at the close of the Triassic. Dinosaurs evolved quickly in the late Triassic, starting off small, and attaining sizes approaching 20 feet (6 m) by the end of the Triassic. The giant pterosaurs were the first known flying vertebrates, appearing late in the Triassic. Crocodiles, frogs, and turtles lived along with the dinosaurs. The end of the Triassic is marked by a major extinction in the marine realm, including total extinction of the conodonts and a mass extinction of the mammal-like reptiles known as therapsids and the placodont marine reptiles. Although the causes of this major extinction event are poorly understood, the timing is coincident with the breakup of Pangaea and the formation of major evaporite and salt deposits. It is likely that this was a tectonic-induced extinction, with supercontinent breakup initiating new oceanic circulation patterns and new temperature and salinity distributions.

After the Triassic-Jurassic extinction, dinosaurs became extremely diverse and many grew quite large. Birds first appeared at the end of the Jurassic. The Jurassic was the time of the giant dinosaurs, which experienced a partial extinction affecting the largest varieties of stegosauroids, sauropods, and the marine ichthyosaurs and plesiosaurs. This major extinction is also poorly explained but may be related to global cooling. The other abundant varieties of dinosaurs continued to thrive through the Cretaceous.

The Cretaceous-Tertiary (K-T) extinction is perhaps the most famous of mass extinctions because the dinosaurs perished during this event. The Cretaceous land surface of North America was occupied by bountiful species, including herds of dinosaurs both large and small, some herbivores, and other carnivores. Other vertebrates included crocodiles, turtles, frogs, and several types of small mammals. The sky had flying dinosaurs, including the vulture-like pterosaurs, and insects, including giant dragonflies. The dinosaurs had dense vegetation to feed on, including the flowing angiosperm trees, tall grasses, and many other types of trees and flowers. Life in the ocean had evolved to include abundant bivalves, including clams and oysters, ammonoids, and corals that built large reef complexes.

Near the end of the Cretaceous, though the dinosaurs and other life-forms did not know it, things were about to change. High sea levels produced by mid-Cretaceous rapid seafloor spreading were falling, decreasing environmental diversity, cooling global climates, and creating environmental stress. Massive volcanic outpourings in the Deccan traps and the Seychelles formed as the Indian Ocean rifted apart and magma rose from an underlying mantle plume. Massive amounts of greenhouse gases were released, raising temperatures and stressing the environment. Many marine species were going extinct, and others became severely stressed. Then one day a visitor from space about six miles (10 km) across slammed into the Yucatán Peninsula of Mexico, instantly forming a fireball 1,200 miles (2,000 km) across, followed by giant tsunamis perhaps thousands of feet (hundreds of meters) tall. The dust from the fireball plunged the world into a dusty fiery darkness with months or years of freezing temperatures, followed by an intense global warming. Few species handled the environmental stress well, and more than a quarter of all the plant and animal kingdom families, including 65 percent of all species on the planet, became extinct forever. Dinosaurs, mighty rulers of the Triassic, Jurassic, and Cretaceous, were gone forever. Oceanic reptiles and ammonoids died off, and 60 percent of marine planktonic organisms went extinct. The great K-T extinctions affected not only the numbers of species, but also the living biomass—the death of so many marine plankton species alone amounted to 40 percent of all living matter on Earth at the time. Similar punches to land-based organisms decreased the overall living biomass on the planet to a small fraction of what it was before the K-T one-two-three knockout blows.

Some evidence suggests that the planet is undergoing the first stages of a new mass extinction. In the past 100,000 years, the ice ages have led to glacial advances and retreats, sea level rises and falls, the appearance and rapid explosion of human (*Homo sapiens sapiens*) populations, and the mass extinction of many large mammals. In Australia 86 percent of large (>100 pounds) animals have become extinct in the past 100,000 years, and in South America, North America, and Africa the extinction is an alarming 79 percent, 73 percent, and 14 percent. This ongoing mass extinction appears to be the result of cold climates and more importantly, predation and environmental destruction by humans. The loss of large-bodied species in many cases has immediately followed the arrival of humans in the region, with the clearest examples being found in Australia, Madagascar, and New Zealand. Similar loss of races through disease and famine has accompanied many invasions and explorations of new lands by humans throughout history.

The history of life on Earth shows that many species exist relatively unchanged for long periods of time and may diversify or become more specialized, in part in response to environmental changes. Occasionally, huge numbers of different species and individuals within species suddenly die off or are killed in mass extinction events. Some of these seem to result from a combination of severe environmental stresses, greatly enhanced volcanism, or a combination of different effects. Most mass extinction events are now known to also be associated with an impact event. However, not all large impact events are associated with a mass extinction, with a prime example being the Manicouagan impact structure, which formed from an impact occuring 214 million years ago, 12 million years older than the Permian-Triassic mass extinction. It seems that mass extinctions may be triggered by a combination of different forces all acting together, including environmental stresses from changes in climate associated with plate tectonics and orbital variations, from massive volcanism, and from impacts of meteorites or comets with Earth.

See also EVOLUTION; IMPACT CRATER STRUCTURES; METEOR, METEORITE.

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mass wasting Mass wasting is the movement of soil, rock, and other Earth materials (together called regolith) downslope by gravity without the direct aid of a transporting medium such as ice, water, or wind. An estimated 2 million or more mass movements occur each year in the United States alone. Mass movements occur at various rates, from a few inches (few centimeters) per year to sudden catastrophic rock falls and avalanches that can bury entire towns under tons of rock and debris. In general, the faster the mass movement, the more hazardous it is to humans, although even slow movements of soil down hill slopes can be extremely destructive to buildings, pipelines, and other construction and infrastructure. In the United States alone, mass movements kill tens of people and cost more than 1.5 billion dollars a year. Other mass movement events overseas have killed tens to hundreds of thousands of people in a matter of seconds. Mass wasting occurs under a wide variety of environmental conditions and forms a continuum with weathering, as periods of intense rain reduce friction between regolith and bedrock, making movement easier. Mass movements also occur underwater, such as the giant submarine landslides associated with the 1964 Alaskan earthquake.

Mass movements are a serious concern and problem in hilly or mountainous terrain, especially for buildings, roadways, and other features engineered into hillsides, in addition to along riverbanks and in places with large submarine escarpments, such as along deltas (like the Mississippi Delta in Louisiana). Seismic shaking and severe storm-related flooding further compound the problem in some prone areas. Imagine building a million-dollar mansion on a scenic hillside, only to find it tilting and sliding down the hill at a few inches (5–10 centimeters) per year. Less spectacular but common effects of slow downhill mass movements are the slow tilting of telephone poles along hillsides and the slumping of soil from oversteepened embankments onto roadways during storms.

Mass wasting is becoming more of a problem as the population moves from the overpopulated flat land to new developments in hilly terrain. In the past, small landslides in the mountains, hills, and canyons were not a serious threat to people, but now large numbers of people live in landslide-prone areas, thus landslide hazards and damage are rapidly increasing.

DRIVING FORCES OF MASS WASTING

Gravity is the main driving force behind mass-wasting processes, as it is constantly attempting to force material downhill. On a slope, gravity can be resolved into two components, one perpendicular to the slope, and one parallel to the slope. The steeper the angle of the slope, the greater the influence of gravity. The effect of gravity reaches a maximum along vertical or overhanging cliffs.

The tangential component of gravity tends to pull material downhill, resulting in mass wasting. When gt (the tangential component of gravity) is great enough to overcome the force of friction at the base of the loose mass, it falls downhill. The friction is really a measure of the resistance to gravity—the greater the friction, the greater the resistance to gravity's pull. Lubrication of surfaces in contact greatly reduces friction, allowing the two materials to slide past one another more easily. Water is a common lubricating agent, so mass-wasting events tend to occur more frequently during times of heavy or prolonged rain. For a mass-wasting event or a mass movement to occur, the lubricating forces must be strong enough to overcome the resisting forces that tend to hold the boulder (for example) in place against the wishes of gravity. Resisting forces include the cohesion between similar particles (like one clay molecule to another) and the adhesion between different or unlike particles (like the boulder to the clay beneath it). When the resisting forces are greater than the driving force (tangential component of gravity), the slope is steady and the boulder stays in place. When lubricating components reduce the resisting forces so much that the driving forces are greater than the resisting forces, slope failure occurs.

The process of the movement of regolith downslope (or under water) may occur rapidly, or it may proceed slowly. In any case, slopes on mountainsides typically evolve toward steady state angles, known as the angle of repose, balanced by material moving in from upslope, and out from downslope. The angle of repose is also a function of the grain size of the regolith.

Human activity can also increase driving forces for mass wasting. Excavation for buildings, roads, or other cultural features along the lower portions of slopes may actually remove parts of the slopes, causing them to become steeper than they were before construction and to exceed the angle of repose. This will cause the slopes to be unstable (or metastable) and susceptible to collapse. Building structures on the tops of slopes will also destabilize them, as the extra weight of the building adds extra stresses to the slope that could initiate the collapse of the slope.

PHYSICAL CONDITIONS THAT CONTROL MASS WASTING

Many factors control whether or not mass wasting occurs and, if it does, the type of mass wasting. These include characteristics of the regolith and bedrock, the presence or absence of water, overburden, angle of the slope, and the way that the particles are packed together.

Preexisting weaknesses in the rock that facilitate movement along them strongly influence mass wasting in solid bedrock terrain. For instance, bedding planes, joints, and fractures, if favorably oriented, can act as planes of weakness along which giant slabs of rock may slide downslope. Rock or regolith containing many pores, or open spaces between grains, is weaker than a rock without pores, because no material fills the pores, whereas if the open spaces were filled the material in the pore space could hold the rock together. Furthermore, pore spaces allow fluids to pass through the rock or regolith, and the fluids may further dissolve the rock, creating more pore space, and further weakening the material. Water in open pore space may also exert pressure on the surrounding rocks, pushing individual grains apart, making the rock weaker.

Water can either enhance or inhibit movement of regolith and rock downhill. Water inhibits downslope movement when the pore spaces are only partly filled with water and the surface tension (bonding of water molecules along the surface) acts as an additional force holding grains together. The surface tension bonds water grains to each other, water grains to rock particles, and rock particles to each other. An everyday example of how effective surface tension may be at holding particles together is found in sand castles at the beach—when the sand is wet, tall towers can be constructed, but when the sand is dry, only simple piles of sand can be made.

Water more typically acts to reduce the adhesion between grains, promoting downslope movements. When the pore spaces are filled, the water acts as a lubricant and exerts forces that push individual grains apart. The weight of the water in pore spaces also exerts additional pressure on underlying rocks and soils, known as loading. When the loading from water in pore spaces exceeds the strength of the underlying rocks and soil, the slope fails, resulting in a downslope movement.

Another important effect of water in pore spaces occurs when the water freezes; freezing causes the water to expand by a few percent, and this expansion exerts enormous pressures on surrounding rocks, in many cases pushing them apart. The freeze-thaw cycles found in many climates are responsible for many of the downslope movements.

Steep slopes are less stable than shallow slopes. Loose unconsolidated material tends to form slopes at specific angles that range from about 33–37 degrees, depending on the specific characteristics of the material. The arrangement or packing of the particles in the slope is also a factor; the denser the packing, the more stable the slope.

PROCESSES OF MASS WASTING

Mass movements are of three basic types, distinguished from each other by the way that the rock, soil, water, and debris move. Slides move over and in contact with the underlying surface, while flows include movements of regolith, rock, water, and air in which the moving mass breaks into many pieces that flow in a chaotic mass movement. Falls move freely through the air and land at the base of the slope or escarpment. A continuum exists between different processes of mass wasting, but many differ in terms of the velocity of downslope movement and also in the relative concentrations of sediment, water, and air. A landslide is a general name for any downslope movement of a mass of bedrock, regolith, or a mixture of rock and soil and indicates any mass wasting process.

A slump is a type of sliding slope failure in which a downward and outward rotational movement of rock or regolith occurs along a concave upslip surface. This produces either a singular or a series of rotated blocks, each with the original ground surface tilted in the same direction. Slumps are especially common after heavy rainfalls and earthquakes and are common along roadsides and other slopes that have been artificially steepened to make room for buildings or other structures. Slump blocks can continue to move after the initial sliding event, and in some cases this added slippage is enhanced by rainwater that falls on the back-tilted surfaces, infiltrates along the fault, and acts as a lubricant for added fault slippage.

A translational slide is a variation of a slump in which the sliding mass moves not on a curved surface, but moves downslope on a preexisting plane, such as a weak bedding plane or a joint. Translational slides may remain relatively coherent or break into small blocks forming a debris slide.

When mixtures of rock debris, water, and air begin to move under the force of gravity, they are said to flow. This is a type of deformation that is continuous and irreversible. The way in which this mixture flows depends on the relative amounts of solid, liquid, and air, the grain size distribution of the solid fraction, and the physical and chemical properties of the sediment. Mass-wasting processes that involve flow are transitional within themselves, and to stream-type flows in the amounts of sediment/water and in velocity. Many names for the different types of sediment flows include slurry flows, mudflows, debris flows, debris avalanches, earthflows, and loess flows. Many mass movements begin as one type of flow and evolve into another during the course of the mass-wasting event. For instance, flows commonly begin as rock falls or debris avalanches and evolve into debris flows or mudflows, as the flow picks up water and debris and flows over differing slopes along its length.

Creep is the slow, downslope-flowing movement of regolith; it involves the very slow plastic deformation of the regolith, as well as repeated microfracturing of bedrock at nearly imperceptible rates. Creep occurs throughout the upper parts of the regolith, and there is no single surface along which slip has occurred. The rates range from a fraction of an inch (about a centimeter) per year up to about two inches (five cm) per year on steep slopes. Creep accounts for leaning telephone poles, fences, and many of the cracks in sidewalks and roads. Although creep is slow and not very spectacular, it is one of the most important mechanisms of mass wasting, accounting for the greatest total volume of material moved downhill in any given year. One of the most common creep mechanisms is through frost heaving, an extremely effective means for moving rocks, soil, and regolith downhill. The ground freezes and ice crystals form and grow, pushing rocks upward perpendicular to the surface. As the ice melts in the freeze-thaw cycle, gravity takes over and the pebble or rock moves vertically downward, ending up a fraction of an inch (centimeter) downhill from where it started. Other mechanisms of surface expansion and contraction, such as warming and cooling, or the expansion and contraction of clay minerals with changes in moisture levels can also initiate creep. In a related phenomenon, the freeze-thaw cycle can push rocks upward through the soil profile, as revealed by farmers' fields in New England and other northern climates, where the fields seem to grow boulders. The fields are cleared of rocks, and years later, the same fields are filled with numerous boulders at the surface. In these cases, the freezing forms ice crystals below the boulders that push them upward; during the thaw cycle, the ice around the edges of the boulder melts first, and mud and soil seep down into the crack, finding their way beneath the boulder. This process, repeated over years, is able to lift boulders to the surface, keeping the northern farmer busy.

The operation of the freeze-thaw cycle makes rates of creep faster on steep slopes than on gentle slopes, with more water, and with greater numbers of freeze-thaw cycles. Rates of creep of up to half an inch (1 cm) per year are common.

Solifluction, the slow viscous downslope movement of water-logged soil and debris, is most common in polar latitudes where the top layer of permafrost melts, resulting in a water-saturated mixture resting on a frozen base. This process is also common to very wet climates, as found in the Tropics. Rates of movement are typically an inch or two (2.5–5 cm) per year, slightly faster than downslope flow by creep. Solifluction results in distinctive surface features, such as lobes and sheets, carrying the overlying vegetation; sometimes the lobes override each other, forming complex structures. Solifluction lobes are relatively common sights on mountainous slopes in wet climates, especially in areas with permafrost. The frozen layer beneath the soil prevents drainage of water deep into the soil or into the bedrock, so the uppermost layers in permafrost terrains tend to be saturated with water, aiding solifluction.

A slurry flow is a moving mass of sediment saturated in water that is transported with the flowing mass. The mixture is so dense that it can suspend large boulders or roll them along the base. When slurry flows stop moving, the resulting deposit therefore consists of a nonsorted mass of mud, boulders, and finer sediment.

Debris flows involve the downslope movement of unconsolidated regolith, most of which is coarser than sand. Some debris flows begin as slumps, but then continue to flow downhill as debris flows. They fan out and come to rest when they emerge out of steeply sloping mountain valleys onto lower-sloping plains. Rates of movement in debris flows vary from several feet (1 m) per year to several hundred miles (kilometers) per hour. Debris flows are commonly shaped like a tongue with numerous ridges and depressions. Many form after heavy rainfalls in mountainous areas, and the number of debris flows is increasing with greater deforestation of mountain and hilly areas. This is particularly obvious on the island of Madagascar, where deforestation in places is occurring at an alarming rate, removing most of the island's trees. What was once a tropical rain forest is now a barren (but geologically spectacular) landscape, carved by numerous landslides and debris flows that bring the terra rossa soil to rivers, making them run red to the sea.

Most debris flows that begin as rock falls or avalanches move outward in relatively flat terrain less than twice the distance they fell. Internal friction (between particles in the flow) and external friction (especially along the base of the flow) slow them. Some of the largest debris flows that originated as avalanches or debris falls travel exceptionally large distances at high velocities—these are debris avalanches and sturzstrom deposits.

Mudflows resemble debris flows, except that they have higher concentrations of water (up to 30 percent), making them more fluid, with a consistency ranging from soup to wet concrete. Mudflows often start as a muddy stream in a dry mountain canyon. As it moves it picks up more and more mud and sand, until eventually the front of the stream is a wall of moving mud and rock. When this comes out of the canyon, the wall commonly breaks open, spilling the water behind it in a gushing flood, which moves the mud around on the valley floor. These types of deposits form many of the gentle slopes at the bases of mountains in the southwestern United States.

Mudflows have also become a hazard in highly urbanized areas such as Los Angeles, where most of the dry riverbeds have been paved over and development has moved into the mountains surrounding the basin. The rare rainfall events in these areas then have no place to infiltrate, and they rush rapidly into the city, picking up all kinds of street mud and debris and forming walls of moving mud that cover streets and low-lying homes in debris. Unfortunately, after the storm rains and waters recede, the mud remains and hardens in place. Mudflows are also common with the first heavy rains after prolonged droughts or fires, as many residents of California and other western states know. After the drought and fires of 1989 in Santa Barbara, California, heavy rains brought mudflows down out of the mountains, filling the riverbeds and inundating homes with many feet of mud. Similar mudflows followed the heavy rains in Malibu in 1994, which remobilized barren soil exposed by the fires of 1993. Three to four feet (more than a meter) of mud filled many homes and covered parts of the Pacific Coast highway. Mudflows are part of the natural geologic cycle in mountainous areas, and they serve to maintain equilibrium between the rate of uplift of the mountains and their erosion. Mudflows are catastrophic only when people have built homes, highways, and businesses in their paths.

Volcanoes, too, can produce mudflows. Rain or an eruption easily remobilizes layers of ash and volcanic debris, sometimes mixed with snow and ice, that can travel many tens of miles (kilometers). Volcanic mudflows are known as lahars. Mudflows have killed tens of thousands of people in single events and have been some of the most destructive of mass movements.

Granular flows are unlike slurry flows, in that, in granular flows, the full weight of the flowing sediment is supported by grain to grain contact between individual grains. Earthflows are relatively fast granular flows with velocities ranging from three feet per day to 1,180 feet per hour (1 m/day to 360 m/hour).

Rockfalls are the free falling of detached bodies of bedrock from a cliff or steep slope. They are common in areas of very steep slopes, where rockfall deposits form huge deposits of boulders at the base of the cliff. Rockfalls can involve a single boulder, or the entire face of a cliff. Debris falls are similar to rockfalls, but these consist of a mixture of rock and weathered debris and regolith.

Rockfalls have been responsible for the destruction of parts of many villages in the Alps and other steep mountain ranges, and rockfall deposits have dammed many a river valley, creating lakes behind the newly fallen mass. Some of these natural dams have been extended and heightened by engineers to make reservoirs, with examples including Lake Bonneville on the Columbia River and the Cheakamus Dam in British Columbia. Smaller examples abound in many mountainous terrains.

Rockslide is the term given to the sudden downslope movement of newly detached masses of bedrock (or debris slides, if the rocks are mixed with other material or regolith). These are common in glaciated mountains with steep slopes and also in places having planes of weakness, such as bedding planes or fracture planes that dip in the direction of the slope. Like rockfalls, rockslides can form fields of huge boulders coming off mountain slopes. The movement to this talus slope is by falling, rolling, and sliding, and the steepest angle at which the debris remains stable is known as the angle of repose, typically 33–37 degrees for most rocks.

Debris avalanches are granular flows moving at very high velocity and covering large distances. These rare, destructive (but spectacular) events have ruined entire towns, killing tens of thousands of people in them without warning. Some have been known to move as fast as 250 miles per hour (400 km/hr). These avalanches thus can move so fast that they move down one slope, then thunder right up and over the next slope and into the next valley. One theory of why these avalanches move so fast is that when the rocks first fall, they trap a cushion of air, and then travel on top of it like a hovercraft. Two of the worst debris avalanches in recent history originated from the same mountain, Nevados Huascaran, the highest peak in the Peruvian Andes. More than

22,000 people died in these two debris avalanches. Numerous debris avalanches were also triggered by the May 12, 2008, magnitude 7.9 earthquake in China that killed nearly 90,000 people.

SUBMARINE LANDSLIDES

Mass wasting is not confined to the land. Submarine mass movements are common and widespread on the continental shelves, slopes, and rises, and also in lakes. Mass movements under water, however, typically form turbidity currents, which leave large deposits of graded sand and shale. Under water, these slope failures can begin on very gentle slopes, even of < 1°. Other submarine slope failures are similar to slope failures on land.

Slides and slumps and debris flows are also common in the submarine realm. Submarine deltas, deep-sea trenches, and continental slopes are common sites of submarine slumps, slides, and debris flows. Some of these are huge, covering hundreds of square miles (<500 km^2). Many of the mass-wasting events that produced these deposits must have produced large tsunamis. The continental slopes are cut by many canyons, produced by submarine mass-wasting events, which carried material eroded from the continents into the deep ocean basins.

Triggering Mechanisms for Submarine Mass Wasting

Submarine mass-wasting events are triggered by many phenomena, some similar to those in the subaerial realm and some different. Shaking by earthquakes and displacement by faulting can initiate submarine mass-wasting events, as can rapid release of water during sediment compaction. High sedimentation rates in deltas, continental shelves and slopes, and other depositional environments may create unstable slopes that can fail spontaneously or through triggers including agitation by storm waves. In some instances, sudden release of methane and other gases in the submarine realm may trigger mass-wasting events.

Submarine landslides tend to be larger than avalanches that originate above the water line. Many submarine landslides are earthquake-induced, whereas others are triggered by storm events and by increases in pressure induced by sea-level rise on the sediments on passive margins or continental shelves. A deeper water column above the sediments on shelf or slope environment can significantly increase the pressure in the pores of these sediments, causing them to become unstable and slide downslope. Since the last glacial retreat 6,000–10,000 years ago, sea levels have risen by 320–425 feet (98–130 m), which has greatly increased the pore pressure on continental slope sediments around the world. This increase in pressure is thought to have initiated many submarine landslides, including the large Storegga slides from 7,950 years ago off the coast of Norway.

Many areas beneath the sea are characterized by steep slopes, including areas along most continental margins, around islands, and along convergent plate boundaries. Sediments near deep-sea trenches are often saturated in water and close to the point of failure, where the slope gives out and collapses, causing the pile of sediments to suddenly slide down to deeper water depths. When an earthquake strikes these areas large parts of the submarine slopes may give out simultaneously, often generating a tsunami.

Some steep submarine slopes that are not characterized by earthquakes may also be capable of generating huge tsunamis. Recent studies along the east coast of North America, off the coast of Atlantic City, New Jersey, have revealed that large sections of the continental shelf and slope are on the verge of failure. The submarine geology off the coast of eastern North America consists of a pile several thousands of feet (hundreds of m) thick of unconsolidated sediments on the continental slope. These sediments are so porous and saturated with water that the entire slope is near the point of collapsing under its own weight. A storm or minor earthquake may be enough to trigger a giant submarine landslide in this area, possibly generating a tsunami that could sweep across the beaches of Long Island, New Jersey, Delaware, and much of the east coast of the United States. With rising sea levels, the pressure on the continental shelves is increasing, and storms and other events may more easily trigger submarine landslides.

Storms are capable of generating submarine landslides even if the storm waves do not reach and disrupt the seafloor. Large storms are associated with storm surges that form a mound of water in front of the storm that may sometimes reach 20–32 feet (6–10 m) in height. As the storm surge moves onto the continental shelf it is often preceded by a drop in sea level caused by a drop in air pressure, so the storm surge may be associated with large pressure changes on the seafloor and in the pores of unconsolidated sediments. A famous example of a storm surge–induced submarine landslide and tsunami is the catastrophic event in Tokyo, Japan, on September 1, 1923. On this day, a powerful typhoon swept across Tokyo and was followed that evening by a huge submarine landslide and earthquake, which generated a 36-foot- (11-m-) tall tsunami that swept across Tokyo killing 143,000 people. Surveys of the seabed after the tsunami revealed that large sections had slid to sea, deepening the bay in many places by 300–650 feet (91–198 m), and locally by as much as 1,300 feet (396 m). Similar storm-induced slides are known from many continental slopes and delta environments, including the Mississippi delta in the Gulf of Mexico and the coasts of Central America.

Types of Submarine Landslides

Submarine slides are part of a larger group of processes that can move material downslope on the seafloor, including other related processes such as slumps, debris flows, grain flows, and turbidity currents. Submarine slumps are a type of sliding slope failure in which a downward and outward rotational movement of the slope occurs along a concave upslip surface. This produces either a singular or a series of rotated blocks, each with the original seafloor surface tilted in the same direction. Slumps can move large amounts of material short distances in short times and are capable of generating tsunamis. Debris flows involve the downslope movement of unconsolidated sediment and water, most of which is coarser than sand. Some debris flows begin as slumps, but then continue to flow downslope as debris flows. They fan out and come to rest when they emerge out of submarine canyons onto flat abyssal plains on the deep seafloor. Rates of movement in debris flows vary from several feet (1 m) per year to several hundred miles per hour (500 km/hr). Debris flows are commonly shaped like a tongue with numerous ridges and depressions. Large debris flows can suddenly move large volumes of sediment, so are also capable of generating tsunamis. Turbidity currents are sudden movements of water-saturated sediments that move downhill underwater under the force of gravity. These form when water-saturated sediment on a shelf or shallow water setting is disturbed by a storm, earthquake, or some other mechanism that triggers the sliding of the sediment downslope. The sediment-laden sediment/water mixture then moves rapidly downslope as a density current and may travel tens or even hundreds of miles at tens of miles (km) per hour until the slope decreases and the velocity of current decreases. As the velocity of the current decreases, the ability of the current to hold coarse material in suspension decreases. The current drops first its coarsest load, then progressively finer material as the current decreases further.

Many volcanic hot-spot islands in the middle of some oceans show evidence that they repeatedly generate submarine landslides. These islands include Hawaii in the Pacific Ocean, the Cape Verde Islands in the North Atlantic, and Réunion in the Indian Ocean. The shape of many of these islands bears the tell-tale starfish shape with cuspate scars indicating the locations of old curved landslide surfaces. These islands are volcanically active, and lava flows move across the surface, and then cool and crystallize quickly as the lava enters the water. This causes the islands to grow upward as very steep-sided columns, whose sides are prone to massive collapse and submarine sliding. Many volcanic islands are built up with a series of volcanic growth periods followed by massive submarine landslides, effectively widening the island as it grows. However, island growth by deposition of a series of volcanic flows over older landslide scars causes the island to be unstable—the old landslide scars are prone to later slip since they are weak surfaces, and the added stress of the new material piled on top of them makes them unstable. Other processes may also contribute to making these surfaces and the parts of the island above them unstable. For instance, on the Hawaiian Islands volcanic dikes have intruded along some old landslide scars, which can reduce the strength across the old surfaces by large amounts. Some parts of Hawaii are moving away from the main parts of the island by up to 0.5–4 inches (1–10 cm) per year by the intrusion of volcanic dikes along old slip surfaces. Also, many landslide surfaces are characterized by accumulations of weathered material and blocks of rubble, that under the additional weight of new volcanic flows can help to reduce the friction on the old slip surfaces, aiding the generation of new landslides. Therefore, as the islands grow, they are prone to additional large submarine slides that may generate tsunamis.

EXAMPLES OF LANDSLIDE DISASTERS

Mass wasting is one of the most costly of natural hazards, with the slow downslope creep of material causing billions of dollars in damage to properties every year in the United States. Earth movements do not kill many people in most years, but occasionally massive landslides take thousands or even hundreds of thousands of lives. Mass wasting is becoming more of a hazard in the United States as people move in great numbers from the plains into mountainous areas as population increases. This trend is expected to continue in the future, and more mass-wasting events like those described in this chapter may be expected every year. Good engineering practices and understanding of the driving forces of mass wasting will hopefully prevent many mass-wasting events, but it will be virtually impossible to stop the costly gradual downslope creep of material, especially in areas with freeze thaw cycles.

Examining the details of a few of the more significant mass-wasting events of different types, including a translational slide, a rockfall-debris avalanche, a mudflow, and whole scale collapse of an entire region is useful to help mitigate future landslide disasters. In this section lessons that can be learned from each different landslide are discussed with the aim that education can save lives in the future. The table "Significant Landslide Disasters" lists some of the more significant landslide and mass-wasting disasters with

SIGNIFICANT LANDSLIDE DISASTERS

Where	When	Trigger Process	How Many Deaths
Shaanxi Province, China	1556	m. 8 earthquake	830,000
Shaanxi Province, China	1920	earthquake	200,000
Sichuan Province, China	2008	m. 7.9 earthquake	87,587
Nevados Huascarán, Peru	1970	m. 7.7 earthquake	70,000
Nevado del Ruiz, Colombia	1985	volcanic eruption	20,000
Tadzhik Republic	1949	m.7.5 earthquake	12,000–20,000
Honduras, Nicaragua	1998	heavy rain	10,000
Venezuela	1999		10,000
Nevados Huascarán, Peru	1962		4,000–5,000
Vaiont, Italy	1963	heavy rain	3,000
Rio de Janeiro, Brazil	1966–67	heavy rain	2,700
Mount Coto, Switzerland	1618		2,430
Cauca, Colombia	1994	m. 6.4 earthquake	1,971
Serra das Araras, Brazil	1967	heavy rain	1,700
Leyte, Philippines	2006	heavy rain	1,450
Kure, Japan	1945		1,145
Shizuoka, Japan	1958	heavy rain	1,094
Rio de Janeiro, Brazil	1966	heavy rain	1,000
Napo, Ecuador	1987	m. 6.1 and 6.9 earthquakes	1,000

more than 1,000 deaths reported, with a bias toward events of the last 100 years.

Shaanxi, China, January 23, 1556

The deadliest earthquake and mass-wasting event on record occurred in 1556 in the central Chinese province of Shaanxi. Most of the 830,000 deaths from this earthquake resulted from landslides and the collapse of homes built into loess, a deposit of wind-blown dust that covers much of central China. The loess represents the fine-grained soil eroded from the Gobi desert to the north and west and deposited by wind on the great loess plateau of central China. Thus, this disaster was triggered by an earthquake but mass-wasting processes were actually responsible for most of the casualties.

The earthquake that triggered this disaster on the morning of January 23, 1556, leveled a 520-mile-wide area and caused significant damage across 97 counties in the provinces of Shaanxi, Shanxi, Henan, Hebei, Hubei, Shandong, Gansu, Jiangsu, and Anhui. Sixty percent of the population was killed in some counties. There were no modern seismic instruments at the time, but seismologists estimate that the earthquake had a magnitude of 8 on the Richter scale, with an epicenter near Mount Hua in Hua County in Shaanxi.

The reason for the unusually high death toll in this earthquake is that most people in the region at the time lived in homes carved out of the soft loess, or silty soil. People in the region would carve homes, called Yaodongs, out of the soft loess, benefit from the cool summer temperatures and moderate winter temperatures of the soil, and also have an escape from the sun and blowing dust that characterizes the loess plateau. The shaking from the magnitude 8 earthquake caused huge numbers of these Yaodongs to collapse, trapping the residents inside. Landslides raced down steep loess-covered slopes, and the long shaking caused the Yaodongs even in flat areas to collapse.

Time tends to make people forget about risks associated with natural hazards. For events that occur only every couple of hundred years, several generations may pass between catastrophic events, and each generation remembers less about the risks than the previous generation. This character of human nature was unfortunately illustrated by another earthquake in central China, nearly 400 years later. In 1920, a large earthquake in Haiyuan, in the Ningxia Authority of northern Shaanxi Province, caused about 675 major landslides in deposits of loess, killing another 100,000–200,000 people. Further south in 2008, the May 12 magnitude 7.9 earthquake in Sichuan Province similarly initiated massive landslides that killed an estimated 87,587 people.

Sichuan Province, China, May 12, 2008

The devastating magnitude 7.9 earthquake in the Longmenshan ranges of Sichuan Province, China, triggered thousands of landslides, including several gigantic landslides that buried several villages and blocked the Qingshui and Hongshi Rivers, forming two lakes, in Donghekou and Shibangou. Two of the first scientists to reach and study the Donghekou landslide after the earthquake were the British geologist Jian Guo Liu and the American geologist T. M. Kusky, who estimated the volume of material that collapsed and buried local villages. They mapped the thickness of the toe of the deposit, the length of the slide (>2 miles, or 3 km) and width (average >2,500 feet or 1 km), and estimated that at least 20–30 million cubic yards (15–25 million m^3) of material raced down the slopes in this single landslide. The staggering reality is that during the earthquake, there were hundreds, if not thousands, of similar giant rock avalanches. The landslides and mass wasting were responsible for a large portion of the known 87,587 deaths from this earthquake.

A mountain on the outskirts of the buried village of Donghekou collapsed, and a large mass of earth slipped downhill at such a high speed it jumped a small mountain, plunged across a river, and then ran a thousand feet (300 m) up a mountain slope across from the village. The top of the mountain has many huge displaced blocks that slid away from the headwall scarp, suggesting that the event started as a massive rock slide/fall, and as the mass moved downhill, it quickly became a debris avalanche as the material in the fall was pulverized into a mixture of large boulders and finer material. Debris from the avalanche formed a natural dam in the river, blocking it and forming an avalanche lake. The scale of this massive landslide is impressive, covering several square miles (km^2) of the surface, and being up to several hundred feet (hundred or more m) thick. The Donghekou landslide is about 30 percent larger than the giant landslide/debris avalanche that buried the community of Barangay Guinsaugon in Leyte, Philippines, on February 17, 2006, killing 1,450 people.

Massive rockfall avalanches and rockflow rubble streams can travel at high speeds over large distances, particularly where a minimum of 650,000 cubic yards (500,000 m^3) of rock falls at least 500 feet (150 m) onto a slope equal to or exceeding 25°. These landslides are able to travel so far because they must conserve mass and momentum. Mapping of the Donghekou landslide by geologists Liu and Kusky suggests that the momentum was maintained by a loss of friction along the base of the landslide, by having the falling mass ride on a cushion of compressed air. The Donghekou and Shibangou landslide avalanches were associated with air blasts that shot out from beneath the falling debris. Rapidly falling rock and soil compressed the air beneath the avalanches and allowed the material to move downhill quickly on a cushion of compressed air for great distances, and as the avalanches came to a halt the air was ejected from beneath the debris in strong jets that knocked down trees in radial patterns reaching a thousand feet (several hundred m) up opposing mountain slopes from the site of the avalanche tongues, in patterns reminiscent of bomb blasts.

The dam blocking the course of Qingshui River was channelled by the army using explosives to allow water to discharge gently, avoiding catastrophic dam collapse and flooding. The devastating consequence of landslides in the region is obvious, with several villages and schools buried by this slide. The landslide in Shibangou also buried a village and blocked the Qingshui River a second time, forming another lake upstream. The landslide at Shibangou is interesting in that the amphitheatre-shaped headscarp detachment surface at the top of the slide is visible, and it shows a typical slumplike crown with transverse cracks and fault zones, large slide blocks moving into the main slide, back rotation of slump blocks on the upper part of the slide, then a transition where the slide turns into an avalanche and eventually a debris avalanche grading into a debris field. This slide was also associated with powerful airblasts, as the trees are blown over in complex patterns going uphill and down valley away from the toe of the avalanche.

Vaiont, Italy, October 9, 1963

One of the worst translational slides ever occurred in Vaiont, Italy, in 1963. In 1960 a large dam was built in a deep valley in northern Italy. The valley occupies the core of a synclinal fold in which the limestone rock layers dip inward toward the valley center and form steeply dipping bedding surfaces along the valley walls. The valley floor was filled with glacial sediments left as the glaciers from the last ice age melted a few thousand years ago. The bottom of the valley was oversteepened by downcutting from streams, forming a steep V-shaped valley in the middle of a larger U-shaped glacial valley. The rocks on the sides of the valley are highly fractured, and broken into many individual blocks, and there was an extensive cave network carved in the limestones. The reservoir behind the dam held approximately 500 million cubic feet (14 million m^3) of water.

After the dam was constructed the pores and caves in the limestone filled with water, exerting extra, unanticipated pressures on the valley walls and dam. Heavy rains in the fall of 1963 made the problem worse, and authorities predicted that sections of the valley might experience landslides. The rocks on the slopes surrounding the reservoir began creeping downhill, first at a quarter inch per day (0.3–0.65 cm/day), then accelerating to one and a half inches per day (4 cm per day) by October 6. Even though authorities were expecting landslides, they had no idea of the scale of what was about to unfold.

At 10:41 P.M., on October 9, 1963, a 1.1-mile- (1.8-km-) long and 1-mile- (1.6-km-) wide section of the south wall of the reservoir suddenly failed, and slid into the reservoir at more than 60 miles per hour (96 km/hr). Approximately 9.5 billion cubic feet (270,000,000 m^3) of debris fell into the reservoir, creating an earthquake shock and an air blast that shattered windows and blew roofs off nearby houses. The debris that fell into the reservoir displaced a huge amount of water, and a series of monstrous waves was generated that raced out of the reservoir devastating nearby towns. A 780-foot- (238-m-) tall wave moved out of the north side of the reservoir, followed by a 328-foot- (100-m-) tall second wave. The waves combined and formed a 230-foot- (70-m-) tall wall of water that moved down the Vaiont Valley, inundating the town of Longarone, where more than 2,000 people were killed by the fast-moving floodwaters. Other waves bounced off the walls of the reservoir and emerged out the upper end of the reservoir, smashing into the town of San Martino, where another 1,000 people were killed in the raging waters.

Landslides in the Andes Mountains; Nevados Huascarán, Peru, 1962, 1970

The Andes, a steep mountain range in South America, are affected by frequent earthquakes and volcanic eruptions, are glaciated in places, and experience frequent storms from being close to the Pacific Ocean. All of these factors combine, resulting in many landslides and related mass-wasting disasters in the Andes. Some of the most catastrophic landslides in the Andes have emanated from Nevados Huascarán, a tall peak on the slopes of the Cordillera Blanca in the Peruvian province of Ancash. In 1962, a large debris avalanche with an estimated volume of 16,900,000 cubic yards (13,000,000 m^3) rushed down the slopes of Nevados Huascarán at an average velocity of 105 miles per hour (170 km/hr). The debris avalanche buried the village of Ranrahirca, killing 4,000–5,000 people. This scene of devastation was to be repeated eight years later. On May 31, 1970, a magnitude 7.7 earthquake was centered about 22 miles (35 km) offshore of Chimbote, a major Peruvian fishing port, causing widespread destruction and about 3,000 deaths in Chimbote. The worst destruction, however, was caused by a massive debris avalanche that rushed off Nevados Huascarán at 174 miles per hour (280 km/hr). This debris flow had a volume of 39–65,000,000 cubic yards (30–50,000,000 m^3), and rushed through the Callejón de Huaylas, a steep valley that runs parallel to the coast. The debris avalanche covered the town of Yungay under thick masses of boulders, dirt, and regolith. Seventy percent of the buildings in the town were covered with tens of feet of debris. The death toll was enormous—most estimates place the deaths at 18,000, although local officials say that 20,000 died in Yungay alone, and as many as 70,000 people died in the region from the landslides associated with the May 31, 1970, earthquake.

There have been many other landslide disasters in the Andes Mountains. In 1974, a rock slide-debris avalanche in the Peruvian province of Huancavelica buried the village of Mayunmarca, killing 450 people. The debris avalanche raced down the mountain with an average velocity of 140 km/hr and caused the failure of a 150-meter-high older landslide dam, initiating major downstream flooding. Debris with a volume of 16,000,000,000 cubic meters from the 1974 avalanche blocked the Mantaro River, creating a new lake behind the deposit. In 1987, the Reventador landslides in Napo, Ecuador, were triggered by two earthquakes with magnitudes of 6.1 and 6.9. These earthquakes mobilized 98,000,000–143,000,000 cubic yards (75–110,000,000 cubic m) of soil that was saturated with water on steep slopes. These slides remobilized into major debris flows along tributary and main drainages, killing 1,000 people and destroying many miles (km) of the Trans-Ecuador oil pipeline, the main economic lifeline for the country. The magnitude 6.4 Paez earthquake in Cauca, Colombia, in 1994 also initiated thousands of thin soil slides that grouped together and were remobilized into catastrophic debris flows in the larger drainages. As these raced downstream, 1,971 people were killed, and more than 12,000 people were displaced from their destroyed homes.

Central America—Honduras, El Salvador, Nicaragua, October 1998

Hurricane Mitch devastated the Caribbean and Central America regions from October 24–31, 1998, striking as one of the strongest and most damaging storms to hit the region in more than 200 years. The storm reached hurricane status on October 24, and reached its peak on October 26–27 with sustained winds of 180 miles per hour (288 km/hr). The storm remained stationary off the coast of Honduras for more than 24 hours, then slowly moved inland across Honduras and Nicaragua, picking up additional moisture from the Pacific Ocean. The very slow forward movement of the storm produced unusually heavy precipitation even for a storm this size. Total amounts of rainfall have been estimated to range between 31–74 inches (80–190 cm) in different parts of the region. Most of the devastation from Mitch resulted from the torrential rains associated with the storm, which continued to fall at a rate of 4 inches (10 cm) per hour even long after the storm moved overland and its winds diminished. The rains from Mitch caused widespread catastrophic floods and landslides throughout the region, affecting Honduras, Guatemala, Nicaragua, and El Salvador. These landslides buried people, destroyed property, and clogged drainages with tons of fresh sediment deposited in the rivers. More than 10,000 people were killed by flooding, landslides, and debris flows across the region, with 6,600 of the deaths reported from along the northern seaboard of Honduras. More than 3 million people were displaced from their homes. The crater of Casitas volcano in Nicaragua filled up with water from the storm and ruptured, initiating large debris flows in this region.

The effects of Hurricane Mitch in Central America were unprecedented in the scope of damage from downed trees, floods, and landslides. Honduras suffered some of the heaviest rainfall, with three-day storm totals in the southern part of the country exceeding 36 inches (90 cm). The areas of heaviest rainfall experienced the greatest number of landslides. Most of the landslides were shallow debris flows with average thickness of only 3.3–6.6 feet (1–2 m), with runout distances of up to 1,000 feet (300 m). Landslide density (number of slides in specified area) in the southern part of Honduras reached about 750–800 per square mile (300 km^2). In the capital of Tegucigalpa, most damage was caused by two large slump/earth flows and debris slides, with the largest being the Cerro El Berrinche slump/earthflow that destroyed Colonia Soto and parts of Colonias Catorce de Febrero and El Povenir. This landslide moved about 7,800,000 cubic yards (6 million m^3) of material downhill, damming the Rio Choluteca, creating a reservoir of stagnant, polluted, sewage-filled water behind the newly created dam. This landslide initially moved slowly, so residents were able to be evacuated prior to the time it accelerated and dammed the river. The landslide consisted of three main parts, including a toe of buckled and folded rock and regolith, then upslope a tongue of a mass of regolith that slid across and dammed the Rio Choluteca, and an upper part consisting of a giant slump block. Other rock and debris slides were triggered by erosion of riverbanks by floods, destroying more homes.

In El Salvador flooding effects from the rain from Mitch did more damage than landslides, with landslides being more important in the north near the border with Honduras. Most of the storm-induced landslides in El Salvador were shallow features that displaced unconsolidated surface regolith derived from deep tropical weathering. Most of the landslides did not travel far but moved downhill as coherent masses that stopped at the bases of steep hills, but became highly fragmented by the time they stopped moving. Some landslides were fluid enough to evolve into debris flows that traveled up to several miles (several km) from their sources, moving quickly across low-gradient slopes and into drainage networks. The largest landslide in El Salvador resulting from the rains from Mitch was the Zompopera slide, a translational earth slide that evolved into a debris flow, traveling more than 3.7 miles (6 km) from the slide's source. This slide was a preexisting feature whose growth was accelerated by the rains of Mitch. Other preexisting landslides also were remobilized as earthslides and earthflows, with rounded headscarps and hummocky topography. Landslides in El Salvador did much less damage than landslides in Honduras.

In Nicaragua most of the landslides triggered by the rains from Hurricane Mitch were debris flows. These debris flows ranged from small flows that displaced only a few cubic meters of material to a depth of a few meters that moved a few tens of meters downslope, to larger debris flows covering 96,000 square yards (80,000 m^2) that moved material up to two miles (three km) downslope in channels. The depth of landslide scars shows a clear relationship to the depth of weathered and altered material, with deeper weathering in deeper depths of landslides. In some areas landslides covered 80 percent of the terrain, but the disturbed areas were considerably smaller in most locations. Hurricane Mitch also initiated some slow-moving earthflows that continued to move more than a year after the storm. Mapping of the substrate in Nicaragua has shown that soils and rocks of certain types were more susceptible to landslides than other materials, so risk maps for future rain-induced landslide events can be made.

One of the worst individual mass movement events associated with the torrential rains from Hurricane Mitch was the collapse of the water-filled caldera of Casitas volcano. Water that rushed out of the volcanic caldera as it collapsed mixed with ash, soil, and debris that washed down rivers, destroying much in its path. Approximately 1,560–1,680 people were killed in this disaster, and many more were displaced. Several towns and settlements were completely destroyed and many bridges along the Pan-American Highway were destroyed. This was the worst disaster to affect Nicaragua since the 1972 Managua earthquake.

The Casitas volcano is a convergent margin volcano, part of the Cordillera Maribos volcanic chain that extends from the northern shore of Lake Managua to Chinandega in the south. Casitas is one of five main volcanic edifices and is a deeply dissected composite volcano that has a .6 mile (1 km) diameter crater at its summit. Heavy rainfall from Hurricane Mitch dropped 4 inches (10 cm) of rain per day on the summit starting on October 25, increasing to 8 inches (20 cm) per day by October 27, and reached a remarkable 20 inches (50 cm) per day on October 30, 1998, the day of the avalanche. The normal monthly average rainfall for October is 13 inches (33 cm), so the rainfall on Casitas was more than six times the normal level preceding the avalanche.

The avalanche began along an altered segment of rock along a fault that cuts the volcano about 66–88 yards (60–80 m) beneath the summit. The avalanche and release of water began when a slab of rock, measuring 137 yards (150 m) long, 55 yards (60 m) high, and 18 yards (20 m) thick, broke off this fault zone, and slid down the fault surface at a 45 degree angle toward the southeast. This initial rockslide released about 260,000 cubic yards (200,000 m^3) of rock.

Residents who lived below the volcano and survived reported a sound like a helicopter along with minor ground shaking as the first avalanche was shattered into small pieces as the rock mass slid down the fault plane. For the first 1.3 miles (2 km) the avalanche deposit moved through a narrow valley, forming a mass of moving rock 500–825 feet (150–250 m) wide and 100–200 feet (30–60 m) deep. As the flow moved down the valley it sloshed back and forth from side to side of the valley, bouncing off the steep walls as it roared past at 50 feet (15 m) per second, sending large blocks of rock flying 6–10 feet (2–3 m) into the air as it passed, decapitating trees above the valley floor. As it continued to move down hill the blocks of rock in the avalanche scoured the clay-rich soil from the valley floor, excavating up to 33 feet (10 m) of material and incorporating this into the avalanche deposit. This process increased the volume of the downslope flow by about nine times its initial volume.

About three hours after the initial avalanche, a lahar was generated from the main accumulation of the avalanche rock, about 2 miles (3 km) from the summit and 2 miles (3 km) above the towns of El Porvenir and Rolando Rodriguez. It is likely that the rain and river flow continued to build up in the avalanche deposit until the pressure inside was great enough to break through the debris-blocked front of the deposit. The lahar formed a rapidly moving concentrated flow that was about 10 feet (3 m) thick, and spread across a width of almost a mile (about 1,500 m). As the lahar raced through the towns of El Porvenir and Rolando Rodriguez it destroyed all buildings and signs of human habitation, scouring the soil and moving this with the flow. Approximately 2,000 people are thought to have perished in the lahar that wiped the two towns away, but the death toll is inaccurate since the bodies were removed and burned for sanitary reasons before accurate counts were made. Several other smaller towns were also destroyed, and a large agricultural area, including many livestock, was wiped out.

Many warnings could have been heeded to avoid the Casitas disaster and the destruction of El Porvenir and Rolando Rodriguez. First, the towns were built in a low-lying area on deposits of old lahars, and the geologic risks should have been appreciated before the towns were settled. The incredibly high rainfall totals should have forewarned residents that the risks for landslides and lahars was high, and certainly after the avalanche occurred, stopping only 2 miles (3 km) upstream, the residents should have been evacuated before the lahar surged out of the avalanche deposit. These risks should be assessed, and applied to the other volcanoes in Central America, as similar situations exist in many places in this region.

Leyte, Philippines, February 17, 2006

A massive landslide buried the community of Barangay Guinsaugon in the central Philippines on February 17, 2006, killing an estimated 1,450 people. This landslide is classified as a rockslide-debris avalanche, having started as a rockslide and turning into a debris avalanche as it moved downslope and spread across the adjacent lowland. The debris avalanche apparently rode on a cushion of air trapped beneath the falling regolith, enabling the avalanche to reach speeds of 87 miles per hour (140 km/hr), and completely destroying the village within three to four minutes from the time of the start of the rockslide.

The Philippines are cut by a major fault that strikes through the entire length of the island chain. This fault is active and related to the convergence and left-lateral strike-slip motion between the Philippine plate and the Pacific plate, which is being subducted beneath the islands from the east. The Philippines are tectonically active, have many steep slopes, and experience heavy seasonal rainfall. All these factors can contribute to making slopes unstable, and undoubtedly helped initiate the 2006 landslide. In the region of the massive rockslide-debris avalanche, the Philippine fault strikes north-northwest, and a second fault branches off this toward the southeast. Movement along these faults has uplifted steep mountains, and these slopes show many horseshoe-shaped scars that probably represent a series of landslide scars.

The landslide covered an area of about 3,600,000 square yards (3,000,000 square m), and stretched 2.5 miles (4 km) from the head of the scarp to the toe of the slide. Considering that the thickness of the deposit ranges from about 100 feet (30 m) at the base of the slope of the mountain to 20–23 feet (6–7 m) near the toe of the slide, it is estimated that about 19.5–26 million cubic yards (15–20 million m^3) of material collapsed from the mountain on February 17, 2006, burying the town of Barangay Guinsaugon. The velocity of the flow during the slide has been estimated at 60–87 miles per hour (100–140 km/hr), based on the time survivors remembered the event to take place in and the distance that the material traveled.

The rockslide originated on the fault surface of the Philippine fault zone and excavated a large, horseshoe-shaped amphitheater on the side of the mountain at a height of about 2,228 feet (675 m). Rock and regolith material consisting of a mixture of volcanic and sedimentary formations moved out of the head of the landslide, initially sliding along steeply dipping surfaces of the Philippine fault, leaving large striations known as slickensides parallel to the direction of movement of the slide. Below the head, or crown of the slide, material was deposited and deformed into terraces of regolith that slid along the slip surfaces. As the rockslide reached the base of the scarp, it spread out laterally and deposited a huge fan-shaped mass of regolith that has many ridges, radial cracks, and isolated hills known as hummocks. These characteristics show that the material initially slid along fracture surfaces as a rockslide, then exploded out of the mountain as a debris avalanche that may have ridden on a cushion of air trapped beneath the falling regolith, aiding the high velocity of the flow.

The origin of the Barangay Guinsaugon landslide is uncertain, but several factors seem to have played a role. First, the active tectonics uplifted the steep mountains along the Philippine fault, and the orientation of the fault surfaces were such that many rocks were perched above loose fracture surfaces that dipped toward the open face of the mountain, with the town of Barangay Guinsaugon directly below. The landslide occurred during a period of very heavy rainfall, and the rain may have both lubricated the slip surfaces and filled open pore spaces in the regolith and rock above the slip surface, loading the slip planes beyond their ability to resist sliding. A small earthquake with a magnitude of 2.6 occurred about 15 miles (25 km) west of the head of the slide, at approximately the same time as the slide. The time of the slide is known from a telephone conversation, in which the speaker noted a loud noise, then screamed in fear, and then the line went dead. It is uncertain if such a small earthquake at this distance could initiate the landslide, but the apparent coincidence in time is remarkable. The most likely scenario is that the steep joint surfaces were already overloaded by the weight of the fresh water, and the small amount of shaking from the earthquake was just enough to change a metastable slope into a moving deadly landslide. Other observations suggest that the earthquake may have occurred slightly after the landslide, and may not have been a contributing cause to the disaster.

It appears that as the rockslide surged off the slopes and crashed onto the relatively flat plane below, where the town was located, that it may have trapped a cushion of air that became compressed and surged out beneath the moving debris avalanche. This surge of air moved many houses, even a three-story concrete building, 1650–2000 feet (550–600 m) from where they were built, and deposited them relatively intact, and in the same relative positions as the surrounding buildings. All the buildings that were moved in this fashion moved radially away from the source of the avalanche. Nearly all of the people that survived the debris avalanche were found along the edge of the deposit, where this cushion of air blasted structures and people from where they were, and deposited them 1,800–2,000 feet (550–600 m) away.

When the landslide occurred, it buried most of the town and its residents, including the school, which was full of 250 children and teachers. Cell phone signals and frantic text messages were received from teachers in the school, and there was tremendous hope that the students might be safe in the strong structure of the school building. The messages warned that cold waters were rapidly rising inside the school building, as the avalanche deposit became saturated with rain and river water. Rescue workers immediately focused their attention on trying to locate the site of the school beneath the rubble on the surface, consulting maps, using satellite global positioning systems (GPS), and other instruments such as ground-penetrating radar. Maps for the town were not very accurate, and it was very difficult to use the radar and other instruments, and rescue workers were constantly under the threat of additional landslides and had to be evacuated several times when the risk levels became too high. Still, after a couple of days, the rescue workers thought they had located the position of the school on the rubble on the surface, and called in heavy excavating equipment in the hope of finding survivors. Hopes were high, and high-tech sonic equipment brought in from the American and Malaysian military crews that happened to be in the area detected sounds from the site. Rhythmic beating and scratching was thought to be coming from people trapped in the school. After digging frantically, the workers found no school, and the scope of the tragedy set in, with little hope of finding any additional survivors. After several weeks or surveying, and analyzing data, geologists realized that the school had probably also been moved 1,650–2,000 feet (500–600 m) by the blast of compressed air from the debris avalanche, and like the other buildings that were moved, may have remained intact, and the rescue workers were simply digging in the wrong place as the students and teachers perished. If the nature of the blast of air was better understood, perhaps rescue workers would have focused their efforts looking in the direction the school would have been moved by the air blast preceding the debris avalanche.

REDUCTION OF LANDSLIDE HAZARDS AND DANGERS

To reduce the hazards to people and property from mass wasting, it is necessary to first recognize which areas may be most susceptible to mass wasting and then to recognize the early warning signs that a catastrophic mass-wasting event may be imminent. Some actions can be taken to protect people and valuable property that may be in the way of imminent downslope flows. As with many geological hazards, a past record of downslope flows is a good indicator that the area is prone to additional landslide hazards. Geological surveys and hazard assessments should be completed in mountainous and hilly terrain before construction of homes, roads, railways, power lines, and other features.

Hazards to Humans

From the descriptions of mass-wasting processes and specific events above, it should be apparent that mass wasting presents a significant hazard to humans. The greatest hazards are from building on mountain slopes, which when oversteepened may fail catastrophically. The fastest moving flows present the greatest threat to human life, with examples of the debris avalanches at Vaiont, Italy, in 1963, Nevados Huascarán, Peru, in 1962 and 1970, and the Leyte, Philippines, disaster of 2006 providing grim examples with tens of thousands of deaths. Gradual creep moves cultural and natural features downhill, which accounts for the greatest cumulative amount of material moved through mass-wasting events. These slow flows do not usually hurt people but they do cause billions of dollars in damages every year. Occasionally slow flows will accelerate into fast-moving debris flows, so it is important to monitor areas that may experience accelerated creep. Human-built structures are not designed to move downhill or to be covered in debris, so mass wasting needs to be appreciated and accounted for when designing communities, homes, roads, pipelines, and other cultural features. The best planning involves not building in areas that pose a significant hazard, but if building is done, the hazards should be minimized through slope engineering, as described below.

Prediction of Downslope Flows

What can be done to reduce the damage and human suffering inflicted by mass movements? Greater understanding of the dangers and specific triggers of mass movements can help reduce casualties from individual catastrophes, but long-term planning is needed to reduce the costs from damage to structures and infrastructure inflicted by downslope movements of all types. One approach to reducing the hazards is to produce maps that show areas that have suffered or are likely to suffer from mass movements. These maps should clearly show hazard zones and areas of greatest risk from mass movements, and what types of events may be expected in any given area. These maps should be made publicly available and used for planning communities, roads, pipelines, and other constructions. It is the responsibility of community planners and engineers to determine and account for these risks when building homes, roads, communities and other parts of the nation's infrastructure.

Several factors need to be considered when making risk maps for areas prone to mass movements. First, slopes play a large role in mass movements, so anywhere there is a slope there is a potential for mass movement. In general, the steeper the slope, the greater the potential for mass movements. In addition, any undercutting or oversteepening of slopes (from coastal erosion or construction) increases the chances of downslope movements, and anything that loads the top of a slope (like a heavy building) also increases the chance of initiating a down slope flow. Slopes that are in areas prone to seismic shaking are particularly susceptible to mass flows, and the hazards are increased along these slopes. Slopes that are wet and have a buildup of water in the slope materials are well lubricated and exert extra pressure on the slope material, and are thus more susceptible to failure.

The underlying geology is also a strong factor that influences whether or not a slope may fail. The presence of joints, bedding planes, or other weak-

Slump of former State Highway 287 into Hebgen Lake, Montana, following an earthquake, August 1959 *(USGS)*

nesses increases the chance of slope failure. Additionally, rocks that are soluble in water may have large open spaces and are more susceptible to slope failure.

These features need to be considered when preparing landslide-potential maps, and once a significant landslide potential is determined for an area, it should be avoided for building. If this is not possible, several engineering projects can be undertaken to reduce the risk. The slope could be engineered to remove excess water, decreasing the potential for failure. This can be accomplished through the installation of drains at the top of the slope, and/or the installation of perforated pipes into the slope that help drain the excess water from the slope material, decreasing the chance of slope failure.

Prevention of Downslope Flows

Slopes can be reduced by removing material, reducing the potential for landslides. If this is not possible, the slope can be terraced, which decreases runoff and stops material from falling all the way to the base of the slope. Slopes can also be covered with stone, concrete, or other material that can reduce infiltration of water, and reduce erosion of the slope material. Retaining walls can be built to hold loose material in place, and large masses of rocks can be placed along the base of the slope (called base loading), which serves to reduce the potential of the base of the slope slumping out by increasing the resistance to the movement. Unvegetated slopes can be planted, as plants and roots greatly reduce erosion, and may help soak up some of the excess water in the soil.

If a slope can not be modified, and people must use the area, there are several other steps that may be taken to help reduce the risk to people in the area. Cable nets and wire fences may be constructed around rocky slopes that are prone to rockfalls, and these wire meshes will serve to catch falling rocks before they hit passing cars or pedestrians. Large berms and ditches may be built to catch falling debris, or to redirect mudflows and other earthflows. Rock sheds and tunnels may be built for shelter in areas prone to avalanches, and people can seek shelter in these structures during snow and or rock avalanches.

Monitoring of Active Landslides

What are the signs that need to be watched for that may warn of an imminent mass-wasting event? Areas that have previously suffered mass-wasting events may be most prone to repeated events, so geomorphological evidence for ancient slumps and landslides should be viewed as a warning. It is recognized that seismic activity and periods of heavy rainfall destabilize slopes and are times of increased hazards. Activity of springs can be monitored to detect when the slopes may be saturated and unstable, and features such as wet areas or puddles oriented parallel to an escarpment should be viewed as potential warnings that the slope is saturated and perhaps ready to slide. In some cases, slopes or whole mountains have experienced accelerated rates of creep soon before large mass-wasting events, such as the Vaiont Dam disaster, described above.

The United States Geological Survey, along with other local agencies, has set up some real-time monitoring programs for a few areas in California, Colorado, Washington, and New Mexico that have active landslide features. These systems include a variety of sensors that collect data in all weather conditions, then transmit this information to geological survey computers where the information is automatically processed and made accessible online to local officials, engineers, and emergency managers.

These real-time monitoring systems operate on the principle that changes from slow flows to rapid flows can be fast and may occur during times of bad weather when residents may not be able to observe the outdoor conditions. Real-time monitoring can detect small changes in movement on ground that could be hazardous to be on, and having real-time data can be crucial in saving human lives and property. The continuous data also provides detailed information on the behavior of landslides over time that engineers can use to design controls to slow down or prevent the landslides from moving catastrophically.

Most of the systems involve monitoring of ground movements and water pressures, and how these change in time. The amount and rates of downslope movement can be recorded by extensometers that can detect stretching or shortening of the ground. Extensometers are basically very sensitive instruments that can measure the distance between two points, typically across an area that is moving and one that is not. One type of extensometer would have a tube inside a pipe, with one side anchored to either side of a moving landslide slip surface. As the landslide slips or creeps, the pipes would gradually move apart, and measurements of the amount over time would give the rate of slip. More sophisticated electronic extensometers are commonly used, but operate on the same principle.

Ground vibrations or micro-earthquakes are also commonly monitored along active landslide features. Increases in ground vibrations can be associated with enhanced slip and movement, and geophones buried in the slides are sensitive enough to detect these small vibrations. Groundwater pressure sensors within the slides monitor the groundwater conditions within the slides, and rain gauges record precipitation. High groundwater pressures or rapid changes in groundwater pressure can indicate that the landslide is on the verge of accelerated slip.

The real-time monitoring systems currently in use normally transmit data to the United States Geological Survey every 10 minutes. If there is strong ground motion or other indications of an imminent slide, the data is transmitted immediately, and warnings can be issued to areas at risk. Sites currently being monitored include several in the northern California Coast Ranges, in the Sierra Nevada, in Washington State near Seattle, in New Mexico, and in several places prone to slow landslides and rapid avalanches in Colorado. Active ground movement is occurring in every state in the country, and it is hoped that real-time monitoring programs can be extended to many other active and potentially hazardous sites.

Mitigation of Damages from Downslope Flows

Once a landslide has occurred it is difficult to recover property losses. Some areas in California were once very expensive ocean-view real estate, but once large slumps started moving whole neighborhoods downslope along systems of curved faults, the properties became worthless. The best way to avoid financial and property loss in places like this is to not try to rebuild, as once the land slips in these regions, it takes huge engineering efforts to prevent further movements. Sometimes the only way to prevent additional landslides is to completely reengineer the slopes, changing steep slopes into terraced low-angle hills. Even this type of engineering may not be enough to prevent additional slides, so the best protection is to avoid building on land that has a history of sliding.

Despite these cautions, many new developments in landslide mitigation techniques make living in mountainous or hilly terrain safer. Most early landslide repair and mitigation techniques involved the building and emplacement of buttresses along the toes of landslides to stop their forward advance and emplacement of pipes and other features to promote water drainage from within the slides. Later, in the middle part of the 20th century, as equipment for moving regolith became larger, it became more common to remove entire slide masses from the sides of hills, and to recompact the material to stabilize the slopes. Since the 1990s, new products such as geomembranes and geotextiles that can hold regolith in place and allow water to escape, have greatly increased the ability to stabilize slopes to make them safer from sliding.

The beginning of slope reengineering to prevent or mitigate landslides is thought to have started in the early 1830s, along railroad lines in England and France. With the industrial revolution in the late 1800s, engineers used steam engines to excavate slopes to 1:1 (horizontal to vertical), or a 45-degree slope. Steeper slopes were covered with masonry retaining walls, holding the slopes back with gravity. When slopes failed in downslope movements, they were typically repaired by cutting the slope back to more gentle slopes, or, if space in urban areas did not permit this, the slopes were reinforced with concrete or masonry walls.

After World War II, large earthwork projects were employed in the United States, particularly associated with construction started as a result of the Interstate Highway Act of 1955. At this time, a new style of landslide mitigation became common, that of excavating the entire slipped area, installing subdrainages, then refilling and compacting the slopes with the excavated material. These so-called buttress fills are still the most common form of landslide repair in the United States, and are moderately effective in most cases. Slopes can be modified and slip surfaces removed, and the subdrainages keep pore water pressures to a minimum.

Since the 1990s, new materials have been developed that help engineers mitigate the effects of landslides and reduce the risks of additional slope failures on repaired slopes. These materials are known as geosynthetics and geomembrane materials, and include many individual types of construction and materials. Pavement cloths are tack-coated membranes that are overlain on existing pavement, then paved over. They serve to hold the pavement together but allow water to escape through the membrane. Filter cloths are used beneath roads and railroad ballast and on hillsides to prevent settlement of gravels into the underlying soils. They help to stabilize slopes and prevent hillside drains and other embankments from settling. Liner membranes are impervious to water and can be used to isolate areas of contaminated or clean groundwater from regional groundwater systems. Drainage membranes are constructed as composites of the above materials, and can be used in the construction of retaining walls, combining different effects of not allowing water in some places, and forcing water to drain in others that are less hazardous. Other materials, known as geogrids, can be stretched across slopes, and these materials add strength and support to toes of slopes that might otherwise collapse.

Since the 1960s, soils on slopes have been engineered by mixing materials into the soil so that they have additional strength, much like the natural effect of having abundant roots in a soil. These reinforced earth walls have become common along highways and above retaining walls. In other cases, strong materials are partly buried along the toes of slides or bases of slopes that could potentially fail. These reinforcements are typically designed as grids, increasing the strength of the toe of the slopes so that they are less susceptible to failure. These grids are typically extended into the slope for a distance of about 1.5 times the slope height. In addition, the surfaces of faces of the slopes are wrapped with the reinforcement grids, and then the surface between the grids is planted, further promoting slope stability.

See also EARTHQUAKES; GEOLOGICAL HAZARDS; SOILS; VOLCANO; WEATHERING.

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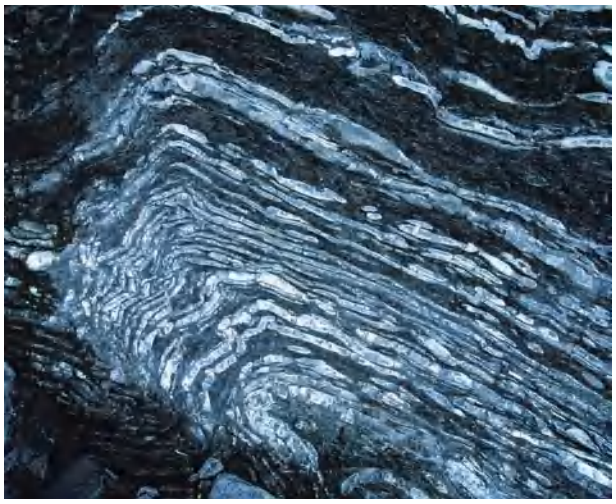

Mélange formed during Taconian Orogeny in the Cambrian Period at Lobster Cove Head, Gros Morne National Park, Newfoundland, Canada *(François Gohier/Photo Researchers, Inc.)*

mélange Mélanges are complex, typically chaotic tectonic mixtures of sedimentary, volcanic, and other types of rocks in a highly sheared sedimentary or serpentinitic matrix. Mélanges show inclusions of material of widely diverse origins at many different scales, showing that mélanges are fractal systems, with the same patterns appearing at multiple scales of observation. Some mélanges may be sedimentary in origin, formed by the slumping of sedimentary sequences down marine escarpments. These mélanges are more aptly termed olistostromes. Tectonic mélanges are formed by structural mixing between widely different units, typically in subduction zone settings.

Tectonic mélanges are one of the hallmarks of convergent margins, yet understanding their genesis and relationships of specific structures to plate kinematic parameters has proven elusive because of the complex and seemingly chaotic nature of these units. Many field workers regard mélanges as too deformed to yield useful information, and simply map the distribution of mélange-type rocks without further investigation. Other workers map clasts and matrix types, search for fossils or metamorphic index minerals in the mélange, and assess the origin and original nature of the highly disturbed rocks. Recent studies have made progress in being able to relate some of the structural features in mélanges to the kinematics of the shearing and plate motion directions responsible for the deformation at plate boundaries.

One of the most persistent questions raised in mélange studies relates to the relative roles of soft-sediment versus tectonic processes of disruption and mixing. Many mélanges have been interpreted as deformed olistostromes or giant submarine landslide deposits, whereas other models attribute disruption entirely to tectonic or diapiric processes. Detailed structural studies have the potential to differentiate between these three end-member models, in that soft-sedimentary and some diapiric processes will produce clasts, which may then be subjected to later strains, whereas purely tectonic disruption will have a strain history beginning with continuous or semicontinuous layers that become extended parallel to initial layering. Detailed field, kinematic, and metamorphic studies may help further differentiate between mélanges of accretionary tectonic versus diapiric origin. Structural observations aimed at these questions should be completed at regional, outcrop, and hand-sample scales.

Analysis of deformational fabrics in tectonic mélange may also yield information about the kinematics of past plate interactions. Asymmetric fabrics generated during early stages of the mélange-forming process may relate to plate kinematic parameters such as the slip vector directions within an accretionary wedge setting. This information is useful for reconstructing the kinematic history of plate interactions along ancient plate boundaries, or how convergence was partitioned into belts of head-on and margin-parallel slip during oblique subduction.

See also ACCRETIONARY WEDGE; CONVERGENT PLATE MARGIN PROCESSES; STRUCTURAL GEOLOGY.

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Mercury The closest planet to the Sun, Mercury, is an astronomical midget. This planet has a mass of only 5.5 percent of the Earth's, a diameter of 3,031 miles (4,878 km), and an average density of 5.4 grams per cubic centimeter. Mercury rotates once on its axis every 59 Earth days and orbits the Sun once every 88 days at a distance of 36 million miles (58 million km). Because it is so close to the Sun, one cannot see it with only the naked eye unless the sun is blotted out, such as just before dawn, after sunset, or during total solar eclipses.

Mercury has such a weak gravitational field that it lacks an atmosphere, although bombardment by the solar wind releases some sodium and potassium atoms from surface rocks, and these may rest temporarily near the planet's surface. The magnetic field is very weak, approximately 1/100th as strong as Earth's. The surface of Mercury is heavily cratered and looks much like the Earth's Moon, showing no evidence for ever having sustained water, dust storms, ice, plate tectonics, or life. The surface of Mercury is less densely cratered than the Moon's, however, and some planetary geologists suggest that the oldest craters may be filled in by volcanic deposits. Some surface scarps, estimated to be more than 4 billion years old, are thought to represent contraction of the surface associated with the core formation and shrinking of the planet in the first half-billion years of its history.

The density of Mercury and the presence of a weak magnetic field suggest that the planet has a differentiated iron-rich core with a radius of approximately 1,118 miles (1,800 km), but it is not known whether this is solid or liquid. A mantle probably exists between the crust and core, extending to 311 to 373 miles (500–600 km) depth. The small size of Mercury means it did not have enough internal energy to sustain plate tectonics or volcanism for long in its history, so the planet has been essentially dead for the past 4 billion years.

See also Earth; Jupiter; Mars; Neptune; Saturn; solar system; Uranus; Venus.

Image mosaic of Mercury. After passing on the dark side of the planet, *Mariner 10* photographed the other, somewhat more illuminated hemisphere of Mercury. Note the rays of ejecta coming from some of the impact craters in the image. The *Mariner 10* spacecraft was launched in 1974. The spacecraft took images of Venus in February 1974 on the way to three encounters with Mercury in March and September 1974 and March 1975. The spacecraft took more than 7,000 images of Mercury, Venus, the Earth, and the Moon during its mission. The Mariner 10 mission was managed by the Jet Propulsion Laboratory for NASA's Office of Space Science in Washington, D.C. *(Image Note: Davies, M. E., S. E. Dwornik, D. E. Gault, and R. G. Strom, Atlas of Mercury, NASA SP-423, 1978; courtesy of NASA)*

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Mesozoic The fourth of five main geological eras, the Mesozoic falls between the Paleozoic and Cenozoic. The total stratigraphic record of rocks deposited in this era, the Mesozoic includes the Triassic, Jurassic, and Cretaceous periods. The era begins at 248 million years ago at the end of the Permian-Triassic extinction event and continues to 66.4 million years ago at the Cretaceous-Tertiary (K-T) extinction event. Named by the British geologist Charles Lyell in 1830, the term means middle life, recognizing the major differences in the fossil record between the preceding Paleozoic era and the succeeding Cenozoic era. Mesozoic life saw the development of reptiles and dinosaurs, mammals, birds, and many invertebrate species that are still flourishing, in addition to flowering plants and conifers inhabiting the land. The era is commonly referred to as the age of reptiles, since they dominated the terrestrial, marine, and aerial environments.

Pangaea continued to grow in the Early Mesozoic, with numerous collisions in eastern Asia, but as the supercontinent grew in some areas, it broke apart in others. As the fragments drifted apart especially in the later part of the Mesozoic, continental fragments became isolated and life-forms began to evolve separately in different places, allowing independent forms to develop, such as the marsupials of Australia. The Atlantic Ocean began opening as arcs and oceanic terranes collided with western North America. In the later part of the Mesozoic, in the Cretaceous, sea levels were high and shallow seas covered much of western North America and central Eurasia, depositing extensive shallow marine carbonates. Many marine organisms such as plankton rapidly diversified and bloomed, and thick organic-rich deposits formed source rocks for numerous coal and oil fields. With the high Cretaceous sea levels, Cretaceous rocks are abundant on many continents and are the most represented of the Mesozoic strata. These strata are rich in fossils that show both ancient and modern features, including dinosaurs and ammonoids, plus newly developed bony fishes and flowering plants. The dinosaurs and reptiles continued to rule the land, sea, and air until the devastating series of events culminating with the collision of an asteroid or comet with Earth at the end of the Cretaceous eliminated the dinosaurs, and caused the extinction of 45 percent of marine genera, including the ammonites, belemnites, inoceramid clams, and large marine reptiles.

See also Cenozoic; Cretaceous; historical geology; paleontology; Paleozoic.

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metamorphism and metamorphic rocks

Metamorphism, a term derived from the Greek, means change of form or shape. Geologists use the term to describe changes in the minerals, chemistry, and texture within a rock. Metamorphism is typically induced by increases in pressure and temperature from burial, regional tectonics, or nearby igneous intrusions.

Any previously formed rocks may be deeply buried by sedimentary cover, affected by regional plate-boundary processes, or be heated close to an igneous intrusion, changing the temperature and pressure conditions from when and where they were formed. *Diagenesis* refers to early changes that occur to rocks, generally below 390°F (200°C). When temperatures rise above 390°F (200°C), the changes become more profound and are referred to as metamorphism.

When sedimentary rocks are deposited they contain many open spaces filled with water-rich fluids. When these rocks are deeply buried and subjected to very high temperatures and pressures, these fluids react with the mineral grains in the rock and play a vital role in the metamorphic changes that occur. These fluids act as a hot, reactive juice that transports chemical elements from mineral to fluids to new minerals. This is confirmed by observations of rocks heated to the same temperature and pressure without fluids, which hardly change at all.

When rocks are heated, certain minerals become unstable and others stabilize. Chemical reactions transform one assemblage of minerals into a new assemblage. Most temperature changes are accompanied by pressure changes, and it is the combined pressure-temperature (P-T) fluid composition that determines how the rock will change.

In liquids, pressures are equal in all directions, but in rocks pressures can be greater or lesser in one direction, and they are referred to as stresses. Textures in metamorphic rocks often reflect stresses that are greater in one direction than in another. Sheets of planar minerals become oriented with their flat surfaces perpendicular to the strongest or maximum stress. This planar arrangement of platy minerals is known as foliation.

Time is also an important factor in metamorphism. In general, the longer the reaction time, the larger the mineral grains and the more complete the metamorphic changes.

GRADES OF METAMORPHISM

Low-grade metamorphism refers to changes that occur at low temperatures and pressures, whereas high-grade metamorphism refers to changes that occur at high temperatures and pressures. At progressively higher grades of metamorphism the high temperature drives the water out of the pore spaces and eventually out of the hydrous mineral structures, so that at very high grades of metamorphism, the rocks contain fewer hydrous minerals (e.g., micas). Prograde metamorphism refers to changes that occur while the temperature and pressure are rising and pore fluids are abundant, whereas retrograde metamorphism refers to changes that occur when temperature and pressure are falling. At this stage, most fluids have already been expelled and the retrograde changes are less pronounced. If this were not so, then all metamorphic rocks would revert back to clays stable at the surface.

METAMORPHIC CHANGES

Compressing a piece of paper would cause the flat dimensions to orient themselves perpendicular to the direction of compression. Likewise, when a metamorphic rock is compressed or stressed, the platy minerals, such as chlorite and micas, orient themselves so that their long dimensions are perpendicular to the maximum compressive stress. The planar fabric that results from this process is known as a foliation.

Slaty cleavage is a specific type of foliation in which the parallel arrangement of microscopic platy minerals causes the rock to break in parallel platelike planes. Schistosity forms at higher metamorphic grades and is a foliation defined by a wavy or distorted plane containing large, visible, oriented minerals such as quartz, mica, and feldspar.

As rocks are progressively heated and subject to more pressure during metamorphism, different mineral assemblages are stable. Even though the rock may retain a stable overall composition, the minerals will become progressively recrystallized and the mineral assemblages (or parageneses) will change under different P-T conditions.

KINDS OF METAMORPHIC ROCKS

The names of metamorphic rocks are derived from their original rock type, their texture, and mineral assemblages. Shales and mudstones have an initial mineral assemblage of quartz, clays, calcite, and feldspar. Slate is the low grade metamorphic equivalent of shale and, with recrystallization, is made of quartz and micas. At intermediate grades of metamorphism, the mica grains grow larger so that individual grains become visible to the naked eye and the rock is called a phyllite. At high grades of metamorphism, the rock (shale, for example) now becomes a schist, which is coarse-grained, and the foliation becomes a bit irregular. Still higher grades of metamorphism separate the quartz and the mica into different layers; this rock is called a gneiss. For both schists and gneisses, a prefix is commonly added to the names to denote some of the minerals present in the rock. For instance, if garnet grows in a biotite schist, it could be named a garnet-biotite schist.

Fresh basalts contain olivine, pyroxene, and plagioclase, none of which contains abundant water. When metamorphosed, however, water typically

Marble (white) and schist (brown) on Charley River in Alaska *(USGS)* enters the rock from outside the system. At low grades of metamorphism, the basalt is turned into a greenstone or greenschist, which has a distinctive color because of its mineral assemblage of chlorite (green) + albite (clear) + epidote (green) + calcite (clear).

At higher metamorphic grades, the greenschist mineral assemblage is replaced by one stable at higher temperature and pressure, typically plagioclase and amphibole, and the rock is known as amphibolite. Amphiboles have a chain structure which gives them an elongated shape. When they crystallize in a different stress field like that found in a metamorphic rock, the new minerals tend to align themselves so that their long axes are parallel to the least compressive stress, forming a lineation. At even higher metamorphic grades the amphiboles are replaced by pyroxenes and the rock is called a granulite.

Limestone metamorphoses into marble, which consists of a network of coarsely crystalline interlocking calcite grains. Most primary features, such as bedding, are destroyed during metamorphism and a new sugary texture appears.

When sandstone is metamorphosed, the silica remobilizes and fills in the pore spaces between the grains, making a very hard rock called a quartzite. Primary sedimentary structures may still be seen through the new mineral grains.

KINDS OF METAMORPHISM

Metamorphism is a combination of chemical reactions induced by changing pressure and temperature conditions and mechanical deformation caused by differential stresses. The relative importance of physical and chemical processes changes with metamorphism in different tectonic settings.

Near large plutons or hot igneous intrusions, rocks are heated to high temperatures without extensive mechanical deformation. These elevated temperatures cause rocks next to plutons to grow new minerals, but these kinds of contact metamorphic rocks may lack strong foliations like those formed during regional metamorphism. Rocks adjacent to these large plutons develop a contact metamorphic aureole of rocks, altered by heat from the intrusion. Large intrusions carry a lot of heat and typically have large contact aureoles, several miles (kilometers) wide.

The contact metamorphic aureole consists of several concentric zones, each with different mineral groups related to higher temperatures closer to the pluton. A hornfels is a hard, fine-grained rock composed of uniform interlocking grains, typically from metamorphosed and suddenly heated shale.

When rocks are buried by the weight of overlying sedimentary rocks, they undergo small changes called diagenesis, until they reach 390°F (200°C). At about 570°F (300°C), some recrystallization may begin, particularly the formation of a group of water-rich minerals known as zeolites.

The most common types of metamorphic rocks are the regional metamorphic rocks. Regional metamorphism involves a combination of chemical and mechanical effects, so these rocks tend to have a pronounced foliation (slate, schist). Most regional metamorphic rocks are found in mountain belts or old eroded mountain belts that formed by the collision of two tectonic plates. In regional metamorphic conditions, the rocks are compressed horizontally, resulting in large folds and faults, which place some rocks on top of other ones, burying them quickly and elevating their pressure and temperature conditions. In this type of environment there is a wide range of pressure/temperature conditions over which the rocks were metamorphosed, and geologists have defined a series of different metamorphic zones reflecting these conditions. These metamorphic zones are each defined by the appearance of a new metamorphic index mineral, which includes, in progressively higher grade order (for shale), chlorite-biotite-garnet-staurolite-kyanite-sillimanite. In the field, the geologist examines the rocks and looks for the first appearance of these different minerals and plots them on a map. By mapping out the distribution of the first appearance of these minerals on a regional scale, the geologists then defines isograds, which are lines on a map marking the first appearance of a given index mineral on the map. The regions between isograds are known as metamorphic zones.

METAMORPHIC FACIES

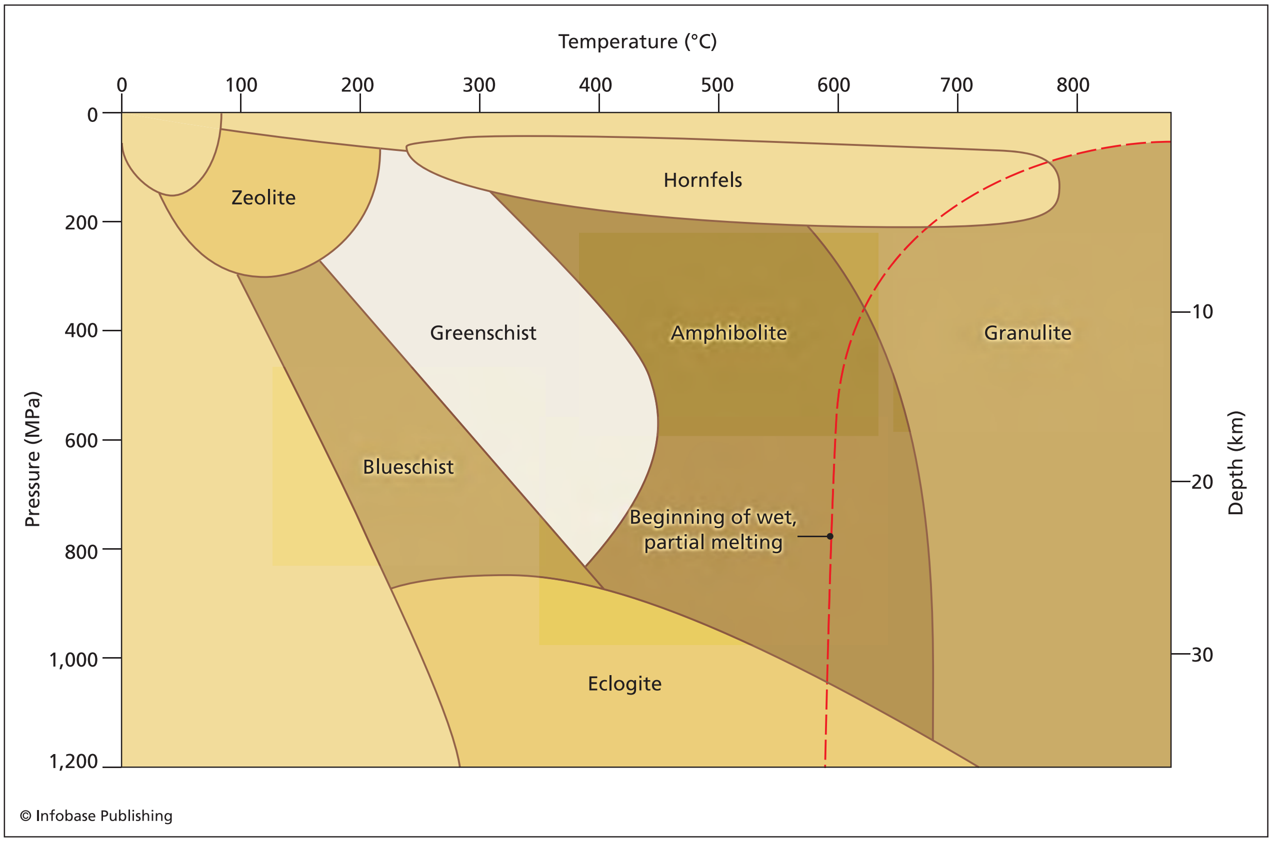
When rocks are metamorphosed their bulk chemistry remains about the same, except for water and CO_2, which are fairly mobile. The mineral assemblages constantly change but the chemistry remains the same. Thus, the temperature and pressure of metamorphism control the mineral assemblages in metamorphic rocks. In 1915, a famous petrologist named Pentti Eskola presented the concept of metamorphic facies, stating that different assemblages of metamorphic minerals that reach equilibrium during metamorphism within a specific range of physical conditions belong to the same metamorphic facies.

Eskola studied rocks of basaltic composition, so he named his facies according to the metamorphic names for basaltic rocks. His classification, shown in the upper figure on page 541, stands to this day.

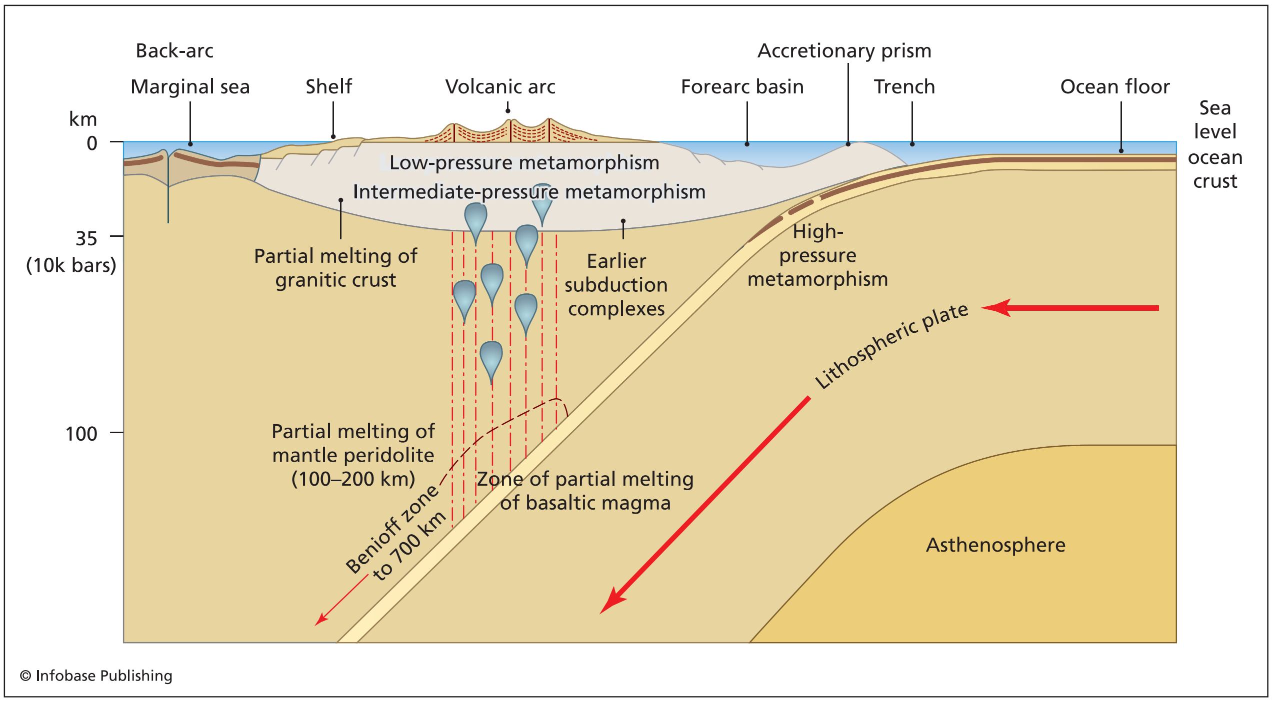
METAMORPHISM AND TECTONICS

Regional metamorphism is a response to tectonic activity, and different metamorphic facies are found in different tectonic environments.

The lower figure on page 541 shows the distribution of metamorphic facies in relationship to the



Metamorphic facies, showing the relationship between pressure, temperature, and different grades of metamorphism



Relationship between metamorphism and tectonics in a convergent margin setting structure of a subduction zone. Burial metamorphism occurs in the lower portion of the thick sedimentary piles that fill the trench, whereas deeper down the trench blue schist facies reflect the high pressures and low temperatures where magmas come up off the subduction slab and form an island arc; metamorphism is of greenschist to amphibolite facies. Closer to the plutons of the arc, the temperatures are high, but the pressures are low, so contact metamorphic rocks are found in this region.

See also MINERAL, MINERALOGY; PETROLOGY AND PETROGRAPHY; PLATE TECTONICS; STRUCTURAL GEOLOGY.

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Stille, Darlene R., Lynn S. Fichter, Terrence E. Young, Jr., and Rosemary G. Palmer. *Metamorphic Rocks: Recycled Rock*. New York; Compass Point Books, 2008.

metasomatic The metamorphic process of changing a rock's composition or mineralogy by the gradual replacement of one component by another through the movement and reaction of fluids and gases in the pore spaces of a rock is called metasomatism, and these processes are metasomatic. Metasomatic processes are responsible for the formation of many ore deposits, which have extraordinarily concentrated abundances of some elements. They may also play a role in the replacement of some limestones by silica, and the formation of dolostones.

Many metasomatic rocks and ore deposits are formed in hydrothermal circulation systems that are set up around igneous intrusions. When magmas, particularly large batholiths, intrude country rocks, they set up a large thermal gradient between the hot magma and the cool country rock. Any water above the pluton gets heated and rises toward the surface, and water from the sides of the pluton moves in to replace that water. A hydrothermal circulation system is thus set up, and the continuous movement of hot waters in such systems often leach elements from some rocks and from the pluton and deposit them in other places, in metasomatic processes.

See also METAMORPHISM AND METAMORPHIC ROCKS.

meteor, meteorite Meteors are rocky objects from space, such as asteroids or smaller rocky objects called meteoroids, that enter the Earth's atmosphere. When meteors pass through Earth's atmosphere, they get heated and their surfaces become ionized, causing them to glow brightly, forming a streak moving across the atmosphere known as a shooting star or fireball. Most meteors burn up before they hit the surface of the Earth, but those that do make it to the surface are then called meteorites.

At certain times of the year, the Earth passes through parts of our solar system that are rich in meteors, and the night skies become filled with shooting stars and fireballs, sometimes as frequently as several per minute. These high-frequency meteor encounters, known as meteor showers, include the Perseid showers that appear around August 11 and the Leonid showers that appear about November 14 (both occur annually).

Many small meteorites have hit the Earth throughout time. Eyewitness accounts describe many meteors streaking across the sky with some landing on the surface. Fragments of meteorites are regularly recovered from the Antarctic ice sheets, where rocky objects on the surface could have come only from space. Although meteors may appear as flaming objects moving across the night skies, they are generally cold icy bodies when they land on Earth, and only their outermost layers get heated from the deep freeze of space during their short transit through the atmosphere.

Meteorites consist of several different main types. Stony meteorites include chondrites, which are very primitive, ancient meteorites made of silicate minerals, like those common in the Earth's crust and mantle, but chondrites contain small spherical object known as chondrules. These chondrules contain frozen droplets of material thought to be remnants of

Iron meteorite from Odessa, Ukraine *(Astrid & Hanns-Frieder Michler/Photo Researchers, Inc.)*

the early solar nebula from which the Earth and other planets initially condensed. Achondrites are similar to chondrites in mineralogy, except they do not contain the chondritic spheres. Iron meteorites are made of an iron-nickel alloy with textures that suggest they formed from slow crystallization inside a large asteroid or small planet that has since been broken into billions of small pieces, probably by an impact with another object. Stony-irons are meteorites that contain mixtures of stony and iron components and probably formed near the core-mantle boundary of the broken planet or asteroid. Almost all meteorites found on Earth are stony varieties.

ORIGIN OF METEORITES AND OTHER EARTH ORBIT-CROSSING OBJECTS

Most meteorites originate in the asteroid belt, situated between the orbits of Mars and Jupiter. At least 1 million asteroids reside in this belt with diameters greater than 0.6 mile (1 km), 1,000 with diameters greater than 18 miles (30 km), and 200 with diameters greater than 60 miles (100 km). Asteroids and meteoroids are distinguished only by their size, asteroids being greater than 328 feet (100 m) in diameter. Meteoroids are referred to as meteors only after they enter the Earth's atmosphere, and as meteorites after they land on the surface. These are thought to be either remnants of a small planet that was destroyed by a large impact event, or perhaps fragments of rocky material that failed to coalesce into a planet, probably due to the gravitational effects of the nearby massive planet of Jupiter. Most scientists favor the second hypothesis, but recognize that collisions between asteroids have fragmented a large body to expose a planetlike core and mantle now preserved in the asteroid belt.

HAZARDS OF METEORITE IMPACT WITH EARTH

The chances of the Earth's being hit by a meteorite are small at any given time, but they are greater than the chances of winning a lottery. The chances of dying from an impact are about the same as dying in a plane crash, for a person who takes one flight per year. These comparisons are statistical flukes, however, and reflect the fact that a large meteorite impact is likely to kill so many people that it raises the statistical chances of dying by impact. A globally catastrophic impact is generally thought of as one that kills more than 25 percent of the world's population, or currently about 1.6 billion people. The Earth has been hit by a number of small impacts and by some very large impacts that have had profound effects on the life on Earth at those times. Most geologists and astronomers now accept the evidence that an impact caused the extinction of the dinosaurs and caused many of the other mass extinctions in Earth history, so it is reasonable to assume that a large impact would have serious consequences for life on Earth. Nations of the world need to consider more seriously the threat from meteorite impacts. Impacts that are the size of the blast that hit Siberia at Tunguska in 1908 happen about once every thousand years, and major impacts, that can seriously affect climate and life on Earth are thought to occur about every 300,000 years. Events like the impact at Chicxulub that killed the dinosaurs and resulted in a mass extinction are thought to occur once every 100 million years. The Chicxulub impact initiated devastating global wildfires that consumed much of the biomass on the planet, and sent trillions of tons of submicrometer dust into the stratosphere. After the flash fires, the planet became dark for many months, the atmosphere and ocean chemistry were changed, and the climate experienced a short-term but dramatic change. The global ecosystem was practically destroyed, and one of the greatest mass extinctions in geological time resulted. Events that approach or exceed this size place the entire population of the world at risk and threaten the survival of the human species. Much smaller events have the potential to destroy agricultural produce in fields around the world, leading to an instant global food shortage and mass starvation, collapse of global economies, and political strife.

There are thousands of near-Earth objects that have the potential to hit the Earth and form impact craters of various sizes. Most of these objects are asteroids diverted from the main asteroid belt and long-period comets. A couple hundred of these objects are in Earth orbit–crossing paths. They range widely in size, density, and composition, all of which can play a role in the type of hazard the body poses as it enters the Earth's atmosphere and falls to the surface. In most instances, for objects greater than several hundred feet (~100 m) in diameter, size is the most important factor, and the controlling factor on the style and hazard of the impact is related to the kinetic energy of the object.

Different hazards are associated with large and minor impacts. Passage of atmospheric shock waves, followed by huge solid Earth quakes, is described, followed by analysis of the tsunamis generated by ocean-hitting impacts. The atmospheric fires associated with the impact, followed by blocking of the Sun by particulate matter thrown up by the impact and fires, is considered to be one of the most hazardous elements of impacts through which many organisms would struggle to survive.

Mitigation strategies for avoiding large impacts of asteroids with Earth involve first locating and tracking objects in Earth orbit–crossing paths. If a collision appears imminent, then efforts should be made to try to deflect the asteroid out of the collision

THE SKY IS ON FIRE

When meteorites pass through Earth's atmosphere, they get heated, and their surfaces become ionized, causing them to glow brightly, forming a streak moving across the atmosphere known as a shooting star or fireball. If the meteorite is large enough, it may not burn up in the atmosphere and will then strike the Earth. Small meteorites may just crash on the surface, but the rare, large object can excavate a large impact crater or cause worse damage. At certain times of the year the Earth passes through parts of the solar system that are rich in meteorites, and the night skies become filled with shooting stars and fireballs, sometimes as frequently as several per minute. These times of high-frequency meteorite encounters are known as meteor showers, and include the Perseid showers that appear around August 11, and the Leonid showers that appear about November 14.

Eyewitness accounts describe many events such as fireballs in the sky recording the entry of a meteorite into the Earth's atmosphere, such as the massive fireball that streaked across western Canada on November 21, 2008, and the huge explosion over Tunguska, Siberia in 1908 that leveled thousands of square miles (km) of trees and created atmospheric shock waves that traveled around the world. Many theories have been proposed for the Tunguska event, the most favored of which is the impact of a comet fragment with Earth.

Few people lived in the core region of the Tunguska explosion in 1908. There were, however, many eyewitness accounts from places near the edges of the core damage zone and from other places as far as Australia and Scandinavia and the United Kingdom. The first published report of the explosion was in the Irkutsk City newspaper on July 2, 1908, published two days after the explosion, as related below:

> The peasants saw a body shining very brightly (too bright for the naked eye) with a bluish-white light. . . . The body was in the form of "a pipe," i.e., cylindrical. The sky was cloudless, except that low down on the horizon, in the direction in which this glowing body was observed, a small dark cloud was noticed. It was hot and dry and when the shining body approached the ground (which was covered with forest at this point) it seemed to be pulverized, and in its place a loud crash, not like thunder, but as if from the fall of large stones or from gunfire was heard. All the buildings shook and at the same time a forked tongue of flames broke through the cloud. All the inhabitants of the village ran out into the street in panic. The old women wept, everyone thought that the end of the world was approaching.

S. B. Semenov, an eyewitness from the village of Vanovara, located about 37 miles (60 km) south of the explosion site, described the event as follows:

> I was sitting in the porch of the house at the trading station of Vanovara at breakfast time . . . when suddenly in the north . . . the sky was split in two and high above the forest the whole northern part of the sky appeared to be covered with fire. At that moment I felt great heat as if my shirt had caught fire; this heat came from the north side. I wanted to pull off my shirt and throw it away, but at that moment there was a bang in the sky, and a mighty crash

course by blasting it with rockets, or mounting rockets on the asteroid to steer it away. Alternatively, if the asteroid is so big, a population from the Earth would need to escape the planet to start a new civilization on a new planet.

Atmospheric Shock Waves

The effect that an asteroid or meteor has on the Earth's atmosphere depends almost completely on the size of the object. Weak meteors that are up to about 30–90 feet (10–30 m) in diameter usually break up into fragments and completely burn up in the atmosphere before they hit the Earth's surface. The height in the atmosphere that these meteors break up depends on the strength of the meteor body, with most comets and carbonaceous chondrites of this size breaking up above 19 miles (30 km). Stronger meteors, such as irons, in this size range may make it to the surface.

Meteors and comets that enter the Earth's atmosphere typically are traveling with a velocity of about six miles/second (10 km/sec), or 21,600 miles per hour (37,754 km/hr). Small meteoroids enter the upper atmosphere every day; more rarely, large ones enter and compress and heat the air in front of them as they race toward the surface. This heat causes most of these bodies to burn up or explode before they reach the surface, with blasts the size of the Hiroshima or Nagasaki atomic bombs happening daily somewhere in the upper atmosphere, by meteors that are about 30 feet (10 m) in diameter. Larger meteors explode closer to the surface and can generate huge

> was heard. I was thrown to the ground about three sajenes [about 23 feet, or 7 m] away from the porch and for a moment I lost consciousness. . . . The crash was followed by noise like stones falling from the sky, or guns firing. The earth trembled, and when I lay on the ground I covered my head because I was afraid that stones might hit it.

Local Inuit people reported the blast, as in the following testimony from Chuchan of the Shanyagir Tribe, recorded by ethnographer I. M. Suslov in 1926:

> We had a hut by the river with my brother Chekaren. We were sleeping. Suddenly we both woke up at the same time. Somebody shoved us. We heard whistling and felt strong wind. Chekaren said, "Can you hear all those birds flying overhead?" We were both in the hut, couldn't see what was going on outside. Suddenly, I got shoved again, this time so hard I fell into the fire. I got scared. Chekaren got scared too. We started crying out for father, mother, brother, but no one answered. There was noise beyond the hut, we could hear trees falling down. Chekaren and I got out of our sleeping bags and wanted to run out, but then the thunder struck. This was the first thunder. The Earth began to move and rock, wind hit our hut and knocked it over. My body was pushed down by sticks, but my head was in the clear. Then I saw a wonder: trees were falling, the branches were on fire, it became mighty bright, how can I say this, as if there was a second sun, my eyes were hurting, I even closed them. It was like what the Russians call lightning. And immediately there was a loud thunderclap. This was the second thunder. The morning was sunny, there were no clouds, our Sun was shining brightly as usual, and suddenly there came a second one!
>
> Chekaren and I had some difficulty getting out from under the remains of our hut. Then we saw that above, but in a different place, there was another flash, and loud thunder came. This was the third thunder strike. Wind came again, knocked us off our feet, struck against the fallen trees.
>
> We looked at the fallen trees, watched the tree tops get snapped off, watched the fires. Suddenly Chekaren yelled "Look up" and pointed with his hand. I looked there and saw another flash, and it made another thunder. But the noise was less than before. This was the fourth strike, like normal thunder.
>
> Now I remember well there was also one more thunder strike, but it was small, and somewhere far away, where the Sun goes to sleep.

All of these observers report a generally similar sequence of events from different perspectives. The bolide formed a giant, columnlike fireball that moved from southeast to northwest across the Siberian sky, then exploded in several pieces high above the ground surface, with audible to deafening sounds, and scorching to noticeable heat. The explosions were followed by the air blast that moved down in the center of the area, then outward toward the edges of the blast zone. These eyewitness accounts provide scientists with some of the best observation of airbursts of this magnitude and serve as a valuable lesson in the behavior of meteorites or asteroids that explode before hitting the surface.

FURTHER READING

Elkens-Tanton, Linda T. *Asteroids, Meteorites, and Comets.* New York: Facts On File, 2006.

Kusky, T. M. *Asteroids and Meteorites: Catastrophic Collisions with Earth.* New York: Facts On File, 2009.

air blasts like the explosion that leveled thousands of square miles (km) of trees in Siberia in 1908.

The flux of meteoroids of different sizes is calculated in part by comparing crater density on the Moon with the expected result in the higher gravity field of the Earth. Larger bodies that make it though the atmosphere hit with a greater frequency for the small objects, and less often for the larger bodies. Meteors in the 30-foot (10-m) diameter range release about as much energy as the nuclear bomb that was dropped on Hiroshima (0.01 megaton [9,070 tonnes]) of TNT equivalent) when they enter the atmosphere and burn before hitting the surface. Events of this size happen about one time per year on Earth, whereas larger events in the 1 megaton (1 megaton = 1,000,000 tons) range occur about once a century, associated with the burning up of 100 foot (30 m) diameter bodies as they plunge through the atmosphere as shown by the table "Effects of Impacts as a Function of Energy and Crater Size."

A moderate-sized impact event, such as a collision with a meteorite with a 5–10 mile (8–16 km) diameter, moving at a moderate velocity of 7.5 miles/sec (12 km/sec), would release energy equivalent to 100 megatons, or about 1,000 times the yield of all existing nuclear weapons on Earth. The meteoroid would begin to glow brightly as it approached Earth, encountering the outer atmosphere. As this body entered the atmosphere, it would create a huge fireball that would crash with the Earth after about 10 seconds. Events of this magnitude happen about

EFFECTS OF IMPACTS AS A FUNCTION OF ENERGY AND CRATER SIZE

Energy of Impact (Megatons)	Diameter of Meteorite or Comet	Crater Diameter Miles (km)	Consequences
< 10			Detonation of stones and comets in upper atmosphere. Irons penetrate to surface
10^1–10^2	245 feet (75 m)	1 (1.5)	Irons form craters (Meteor Crater), Stones produce airbursts (Tunguska). Land impacts destroy an area the size of a city (Washington, Paris)
10^2–10^3	525 feet (160 m)	1.9 (3)	Irons and stones produce ground-bursts, comets produce airbursts. Land impacts destroy an area the size of a large urban area (New York, Cairo)
10^3–10^4	1,150 feet (350 m)	3.7 (6)	Impacts on land produce craters. Ocean impacts produce significant tsunami. Land impacts destroy area size of small state (Delaware, Israel)
10^4–10^5	0.43 miles (0.7 km)	7.5 (12)	Tsunamis reach oceanic scales, exceeding damage from land impacts. Land impacts destroy area size of a moderate state (Virginia, Taiwan)
10^5–10^6	1.06 miles (1.7 km)	18.7 (30)	Land impacts raise enough dust to affect climate, and freeze crops. Ocean impacts generate hemispheric tsunamis. Global destruction of ozone. Land impacts destroy area size of large state (California, France)
10^6–10^7	1.9 miles (3 km)	37 (60)	Both land and ocean impacts raise dust, impact ejecta is global, changes global climate. Widespread fires. Land impacts destroy area size of a large nation (Mexico, India)
10^7–10^8	4.3 miles (7 km)	78 (125)	Global conflagration, prolonged climate effects, probably mass extinction. Direct destruction of continental scale area (United States, Australia)
10^8–10^9	10 miles (16 km)	155 (250)	Large mass extinction (K-T in scale)
10^9–10^{10}			Survival of all life threatened

* Note: table based on David Morrison, Clark Chapman, and Paul Slovic (*The Impact Hazard, 1994*).

once every 1,000 years on Earth, but obviously even in this energy range, impacts are not posing serious threats to the survival of life on Earth.

Objects that break up lower than 12 miles (20 km) above the surface cause much greater destruction. Objects about 165 feet (50 m) in diameter that break up at this height will generate significant airbursts that pose significant hazards. Larger objects will strike the ground, releasing energy in a manner similar to atomic bomb blasts (but without releasing radioactivity), with the amount of energy proportional to the size of the meteorite or comet. The impact that hit Tunguska in 1908 is estimated to have released about 10–20 megatons (9.1–18 megatonnes), with a radius of complete destruction of 15 miles (25 km), and a much larger affected area. The area of destruction increases to the two-thirds power of the magnitude of the blast.

Solid Earth Shock Wave and Earthquakes

When meteorites hit the surface of the Earth they generate seismic waves and cause earthquakes. The size of the earthquake is related to the energy released by the impactor, which is related to its mass and its velocity. The larger the energy released on the surface, the larger the earthquake. Meteors that explode in the atmosphere can also generate earthquakes, as the air blast transfers energy to the surface and also generates seismic waves.

Large impacts generate seismic waves that travel through the interior of the Earth and along the surface layers. For comparison, the Tunguska explosion and airburst generated a seismic event with a Richter magnitude that is estimated to be only about a magnitude 5 earthquake. In contrast, the Chicxulub impact at the Cretaceous-Tertiary boundary generated a magnitude 11, 12, or 13 earthquake, shaking the entire planet, and resulting in seismic waves that uplifted and dropped the ground surface by hundreds to a thousand feet (up to 300 m) at a distance of 600 miles (965 km) from the crater.

If an impact of this size and energy hit the Earth today, shock waves would be felt globally as earthquakes of unimaginable size, destroying much of the surface of the planet, and killing billions of people.

Tsunamis Generated by Meteorite Impacts in the Oceans

If a large meteorite struck the ocean, huge tsunamis would be formed, hundreds and perhaps thousands of feet tall (hundreds of m). These would run up on coastlines, washing away the debris from the earthquakes of a few moments or hours before. Impacts that hit water cause devastation over a larger area than impacts that hit land because of the far-traveling effects of the tsunamis. Impacts that have an energy release of 1,000 megatons (907 megatonnes) should generate tsunamis about 15 feet (5 m) tall and travel more than 600 miles (1,000 km). For impacts that are significantly larger than this (above 10,000 megatons, or 9,070 megatonnes) the damage from the tsunami is much greater, and covers a much larger area than the damage from the blast of the impactor itself. The tsunami associated with the Chicxulub impact on the Yucatán Peninsula may have initially been thousands of feet (hundreds of m) high, washing over much of the Gulf Coast of the United States and Mexico, and devastating the Caribbean.

Global Firestorm and Global Winter

The force of large- and medium-scale impacts ejects enormous quantities of superheated dust and gases into the atmosphere, some of which would fall back to Earth as flaming fireballs. Most of the dust would make it into the upper atmosphere, where it would encircle the entire planet. The energy from the impact would heat the atmosphere to such a degree that it would spontaneously ignite forests and much of the biomass, sending dark clouds of smoke into the atmosphere. This smoke and the dust from the impact would block out the Sun, leading to a rapid plunge into a dark mini-ice age with most of the Sun's energy blocked from reaching Earth, preventing photosynthesis and plant growth. This darkness and cold would last for several months as the dust slowly settled, forming a global layer of dust recording the chemical signature of the impact. The hallmark of such an impact includes a hallmark high concentration of the rare element iridium, produced by vaporization of the meteorite.

Gradually, rain would remove the sulfuric acid and dust from the atmosphere, but the chemical consequences include enhanced acid rain, which rapidly dissolves calcium carbonates from limestone and shells, releasing carbon dioxide to the atmosphere. The acid rain would wreak havoc on the ocean biosphere, changing the ocean chemistry to the point at which many life-forms become extinct. The carbon dioxide released to the atmosphere would heat the planet a few months after the impact, and the planet would enter an extended warm period caused by this greenhouse effect. Temperatures would be more than 10°C (18°F) hotter on average, shifting climate belts and leading to excessively long, hot summers.

MITIGATING THE DANGERS OF FUTURE IMPACTS

Collision of a meteorite about a mile (1.6 km) across with Earth would do enough damage to wipe out about a quarter of the human race, and events of this magnitude may occur approximately every 3 million years. Larger events happen less frequently, and smaller events occur more frequently. An estimated 50 objects with diameters of 50–100 feet (15–30 m) pass between the Earth and Moon every day, though these rarely collide with the Earth. Comets and stony meteorites of this size will typically break up upon entering the atmosphere, whereas iron meteorites would tend to make it all the way to the planet. Luckily, few of the near-Earth objects are iron meteorites.

To date, there have only been limited efforts by the nations of the world to monitor near-Earth objects and to try to prevent large meteorites from crashing into the Earth and wiping out much of the population and biosphere. NASA has estimated that there are about 2,000 near-Earth objects greater than one-half mile (1 km) in diameter and that about half of them may eventually hit the Earth. However, the time interval between individual impacts is greater than 100,000 years. If any of these objects hits the Earth, the death toll will be tremendous, particularly if any of them hit populated areas or a major city.

Collision of Earth with an asteroid only a mile or two (several km) in diameter would release as much energy as that released by the simultaneous explosion of several million nuclear bombs.

It is now technically feasible to map and track many of the large objects that could be on an Earth-impacting trajectory, and this is being done to some degree. Greater efforts would involve considerable expense to advanced societies, principally the taxpayers of the United States. NASA, working with the United States Air Force, has mounted a preliminary program for mapping and tracking objects in near-Earth orbit and has already identified many significant objects. Lawmakers and the public must decide if the calculated risk of the hazards of impacts hitting the Earth is worth greater expense. Risk assessment typically involves many variables, such as the likelihood of an event happening, how many deaths or injuries would result, and what can be done to reduce the risk. Also, other questions need to be asked, such as is it more realistic to try to stop the spread of disease, crime, poverty, and famine and prepare for other natural disasters than to spend resources looking for objects that might one day collide with the Earth. If an asteroid is determined to be on a collision course with Earth, some type of asteroid deflection strategy would need to be employed to attempt to prevent the collision.

Spaceguard is a term that refers to a number of different efforts to search for and monitor near-Earth objects. The United States Congress published a Spaceguard Survey Report, mandating that 90 percent of all large near-Earth objects be located by 2002, and some programs were funded at a level of several million dollars per year toward this goal. Present estimates are that the original goal will be met by the year 2020. One of these efforts is the Catalina Sky Survey, which discovered 310 near-Earth objects in 2005, 400 in 2006, and 450 in 2007. A loose organization of observers and astronomers in several countries meet to discuss strategies, progress, and ideas about asteroid detection through the International Astronomical Union. However, it is noteworthy that these efforts were not sufficient to detect two meteorite impacts with Earth: an explosion over the Mediterranean in 2002 and the crash of a meteorite in the Bodaybo area of Siberia on September 25, 2002. The meteorites were detected by United States military antimissile defense satellites only as they entered the Earth's atmosphere.

Societies have the technology to attempt to divert or blow up a meteorite using nuclear devices. Bombs could be exploded near the asteroid or meteorite in an attempt to move it out of Earth orbit or to break it up into pieces small enough to break up upon entering the atmosphere. Alternatively, given enough time, rockets could be installed on the meteorite and fired to try to steer it out of its impact trajectory. However, many asteroids rotate rapidly, and rockets mounted on these asteroids would not be so effective at changing their course. Other proposals have been made, including firing massive missiles at the asteroid, transferring kinetic energy to move it out of its collision course. However, if the object is very large it is likely that even all of the nuclear weapons or bombs on the planet would not have a significant effect on altering the trajectory of the meteorite or asteroid. Strategies for preventing catastrophic collisions of meteorites with Earth fall into two general categories—those that attempt to destroy or fragment the asteroid into small pieces that would burn up upon passing though the Earth's atmosphere, and those that attempt to divert the asteroid and move it out of its trajectory toward Earth. In some cases it may be enough to simply delay the arrival time of the asteroid with Earth's orbit so that the planet is no longer at the place where it would collide with the asteroid when it crosses Earth's orbit. Such strategies use less energy than blasting the asteroid out of the solar system.

Nuclear Attack

One of the most popular ideas for deflecting asteroids away from a potential collision with Earth is to fire many nuclear missiles at the asteroid, with the idea that the blast would vaporize the asteroid, eliminating the danger. However, the energy requirements may not be attainable with the world's current arsenal of nuclear weapons, as there are currently no nuclear weapons that release enough energy to destroy an asteroid only a half mile (1 km) in diameter. If enough blasts or a large enough blast could be directed at an incoming asteroid, it is likely that the blasts would simply fragment the asteroid into many pieces, which would then fall to Earth along with the radiation from the nuclear explosions.

Instead of aiming nuclear blasts directly at any incoming asteroid, it may be possible to divert the orbit of the asteroid by exploding many nuclear bombs near the asteroid, and the energy released from these blasts could effectively steer the asteroid away from its collision course with Earth. A group of researchers from Massachusetts Institute of Technology published a study called Project Icarus, showing such a strategy to be theoretically possible.

Kinetic Impact Strategies

One of the alternative strategies that may be effective in deflecting an asteroid from Earth's orbit is to send a massive spacecraft to collide with the asteroid, altering its momentum and removing it from the collision course. This strategy is currently the object of a major study and mission, called Don Quijote, by the European Space Agency. Early results from this mission have shown that it is possible, and a model of the deflection of near-Earth asteroid 99942 Apophis shows that it would only take a spacecraft with a mass of less than one ton (0.9 tonne) to deflect the asteroid out of its modeled collision course with Earth.

Gravitational Tractor Strategies

Many asteroids and comets are composed of piles of disconnected rubble. Deflection strategies that rely on kinetic impact or deflection by explosion would not necessarily work on these types of asteroids, since any impact would only deflect the fragment that it directly hit. One alternative type of deflection strategy involves slowly moving these asteroid rubble piles by moving a massive spacecraft near the asteroid and letting the gravitational attraction of the spacecraft slowly pull the asteroid out of threatening orbit. Since both the asteroid and the spacecraft would have a mutual gravitational attraction, the asteroid could be slowly pulled in one direction if small rockets on the spacecraft are used to counter the attraction toward the asteroid, and slowly pull it out of a path dangerous to Earth. This strategy would take several years to be effective.

Other Strategies

A number of other strategies have been proposed that could eventually be developed into working deflection missions for asteroids heading toward Earth. One proposal is to focus solar energy at the surface of the asteroid, vaporizing material from the surface, eventually deflecting it from its collision course. It may be possible to wrap incoming asteroids with reflective sheeting or to add reflective dust to the surface, so that part of the asteroid receives additional radiation from the Sun, and radiation pressure distributed unequally on the asteroid may be enough to deflect it from its orbit. Another idea is to attach to the asteroid a large solar sail, which would absorb solar energy and change its orbit.

RECENT NEAR-COLLISIONS OF ASTEROIDS WITH EARTH

Collisions between asteroids can alter their orbits and cause them to head into an Earth orbit–crossing path. At this point, the asteroid becomes hazardous to life on Earth and is known as an Apollo object. NASA and the United States Air Force estimate that approximately 20,000 objects in space could be on Earth orbit–crossing trajectories. Presently, about 150 Apollo asteroids with diameters of greater than half a mile (1 km) are known, and a couple of thousand objects this size are known in the entire near-Earth object group. Objects larger than 460 feet (140 m) hit the Earth on average about once every 5,000 years. In 1996 an asteroid about one quarter mile (half km) across nearly missed hitting the Earth, speeding past at a distance about equal to the distance to the Moon. The sobering reality of this near collision is that the asteroid was not even spotted until a few days before it sped past Earth. If the object had been bigger or slightly closer, it might not have been stoppable, and its collision might have had major consequences for life on Earth. A similar near miss event was recorded again in 2001; Asteroid 2001 YB5 passed Earth at a distance of twice that to the Moon, and it too was not recognized until two weeks before its near miss. If YB5 hit Earth, it would have released energy equivalent to 350,000 times the energy released during the nuclear bomb blast in Hiroshima.

The objects that are in Earth orbit–crossing paths could not have been in this path for very long, because gravitational influences of the Earth, Mars, and Venus would cause them to hit one of the planets or be ejected from the solar system within about 100 million years. The abundance of asteroids in an Earth orbit–crossing path demonstrates that ongoing collisions in the asteroid belt are replenishing the source of potential impacts on Earth. A few rare meteorites found on Earth have chemical signatures that suggest they originated on Mars and on the Moon, probably being ejected toward the Earth from giant impacts on those bodies.

Other objects from space may collide with Earth. Comets are masses of ice and carbonaceous material mixed with silicate minerals that are thought to originate in the outer parts of the solar system, in a region called the Oort Cloud. Other comets have a closer origin, in the Kuiper Belt just beyond the orbit of Neptune, including the dwarf planet Pluto. Comets may be less common near Earth than meteoroids, but they still may hit the Earth with severe consequences. Astronomers estimate that there are more than a trillion comets in the solar system. Since they are lighter than asteroids and have water-rich and carbon-rich compositions, many scientists have speculated that cometary impact may have brought water, major components of the atmosphere, and even life to Earth. The relative risks of impact for different objects are described in the table "Torino Hazard Scale for Near-Earth Objects."

The importance of monitoring near-Earth objects is highlighted by a number of recent events where asteroids or comets nearly collided with Earth, or exploded in the planet's atmosphere. Several "Tunguska style" atmospheric explosions, where meteorites exploded in the atmosphere and formed air blasts have been noted, including the events in 1930

TORINO HAZARD SCALE FOR NEAR-EARTH OBJECTS

Scale	Description of Hazard
No Hazard	
0	The likelihood of a collision is zero, or is so low as to be effectively zero. Also applies to small objects such as meteors and bodies that burn up in the atmosphere as well as infrequent meteorite falls that rarely cause damage.
Normal	
1	A routine discovery in which a pass near the Earth is predicted but poses no unusual level of danger. Current calculations show the chance of collision is extremely unlikely with no cause for public attention or public concern. New telescopic observations very likely will lead to reassignment to level 0.
Meriting Attention by Astronomers	
2	A discovery, which may become routine with expanded searches, of an object making a somewhat close but not highly unusual pass near the Earth. While meriting attention by astronomers, there is no cause for public attention or public concern as an actual collision is very unlikely. New telescopic observations very likely will lead to reassignment to level 0.
3	A close encounter, meriting attention by astronomers. Current calculations give a 1 percent or greater chance of collision capable of localized destruction. Most likely, new telescopic observations will lead to reassignment to level 0. Attention by public and by public officials is merited if the encounter is less than a decade away.
4	A close encounter, meriting attention by astronomers. Current calculations give a 1 percent or greater chance of collision capable of regional devastation. Most likely, new telescopic observations will lead to reassignment to Level 0. Attention by public and by public officials is merited if the encounter is less than a decade away.
Threatening	
5	A close encounter posing a serious but still uncertain threat of regional devastation. Critical attention by astronomers is needed to determine conclusively whether a collision will occur. If the encounter is less than a decade away, governmental contingency planning may be warranted.
6	A close encounter by a large object posing a serious but still uncertain threat of a global catastrophe. Critical attention by astronomers is needed to determine conclusively whether a collision will occur. If the encounter is less than three decades away, governmental contingency planning may be warranted.
7	A very close encounter by a large object, which if occurring this century, poses an unprecedented but still uncertain threat of a global catastrophe. For such a threat in this century, international contingency planning is warranted, especially to determine urgently and conclusively whether a collision will occur.
Certain Collisions	
8	A collision is certain, capable of causing localized destruction for an impact over land or possibly a tsunami if close offshore. Such events occur on average between once per 50 years and once per several 1,000 years.
9	A collision is certain, capable of causing unprecedented regional devastation for a land impact or the threat of a major tsunami for an ocean impact. Such events occur on average between once per 10,000 years and once per 100,000 years.
10	A collision is certain, capable of causing global climatic catastrophe that may threaten the future of civilization as we know it, whether impacting land or ocean. Such events occur on average once per 100,000 years, or less often.

over the Amazon River, in 1965 over southeastern Canada, in 1965 over Lake Huron, in 1967 in Alberta, Canada, in Russia in 1992, in Italy in 1993, in Spain in 1994, in Russia and the Mediterranean in 2002, and in Washington in 2004. Other asteroid encounters luckily were "near-misses," where larger asteroids narrowly escaped collision with Earth. In 1972, an asteroid estimated to be 6–30 feet (2–10 m) in diameter entered the Earth's atmosphere above Salt Lake City, Utah, formed a huge fireball that raced across the daytime sky, and exited the atmosphere near Calgary in Alberta, Canada. The geometry of the orbit was such that the meteorite just grazed the outer parts of the atmosphere, getting as close to the surface as 36 miles (58 km). In 1989 the 1,000-foot (300-m) diameter Apollo asteroid 4581 Asclepius crossed the exact place the Earth had just passed through six hours earlier, missing the planet by a mere 400,000 miles (700,000 km). If an object that size had collided with Earth, the results would have been catastrophic. On June 14, 2002, a 165–400 foot (50–120 m) diameter asteroid named 2002 MN passed unnoticed at a distance of 75,000 miles (120,700 km), one-third the distance to the moon. Remarkably, this asteroid was not recognized until three days after it passed that closely to the Earth. On July 3, 2006, another asteroid, named 2004 XP14, passed at about 248,000 miles (400,000 km), moving at a velocity of 10.5 miles per second (17 km/sec).

Several asteroids are known to be on near-collision courses with Earth. These include 99942 Apophis, which will pass within 20,000 miles (32,000 km) of Earth but will miss the planet. However, it may come closer in 2036, with a possible impact on that orbit. The chances of impact are estimated to be one in 43,000, making 99942 Apophis a Level O danger on the Torino impact hazard scale. On March 16, 2880, asteroid 29075, with a diameter of 0.7–0.9 miles (1.1–1.4 km) will pass close to Earth. Some models suggest that this asteroid has a one in 300 chance of hitting the planet, posing a significant threat for a catastrophic collision, with major changes to climate and possibly triggering mass extinctions. This asteroid has the highest probability of any known large objects of hitting Earth.

SUMMARY

The chances of experiencing a large meteorite impact on Earth are small, but the risks associated with large impacts are extreme. Small objects hit the Earth many times every day but burn up in the atmosphere. Events that release enough energy to destroy a city happen about once every thousand years, while major impacts that can significantly alter the Earth's climate happen every 300,000 years. Truly catastrophic impacts that cause mass extinctions, death of at least 25 percent of the world's population, and could lead to the end of the human race occur about every 100 million years.

Specific hazards from impacts include atmospheric shock waves and air blasts, major earthquakes, monstrous tsunamis, and global firestorms that throw so much soot in the air the impact is followed by a global winter that could last years. Carbon dioxide can be released by impacts as well and then can act as a greenhouse gas leading to global warming.

More than 20,000 near-Earth objects are thought to have a potential to collide with Earth, and more than 150 of these are larger than half a mile (1 km) across. A variety of programs to detect and track these near Earth objects is under way, yet most meteorite impacts and near collisions in the past few years have been complete surprises. If a large asteroid is found to be on a collision course with Earth, several strategies have been devised that may be able to move the object out of its collision course with Earth. The asteroid could be attacked with nuclear weapons that could vaporize the object, removing the threat. However, this could also break up the asteroid and send thousands of smaller, now radioactive, fragments to Earth. If nuclear weapons are detonated near the asteroid, the force of the explosions may be enough to push it out of its collision course. A massive spacecraft could be crashed into the asteroid, changing its momentum and moving it from orbit. It might be possible to install rocket propulsion systems on the asteroid and have it steer itself out of Earth orbit. A variety of other techniques have been proposed to deflect asteroids, including beaming solar radiation at the body, or attaching thermal blankets or sails, to have the solar radiation pressure move the asteroid out of its collision course.

See also ASTEROID; COMET; SOLAR SYSTEM.

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meteoric Water that has recently come from the Earth's atmosphere is called meteoric water. The term is usually used in studies of groundwater, to distinguish water that has resided in ground for extended periods of time versus water that has recently infiltrated the system from rain, snow melt, or stream infiltration. Measurements of oxygen isotopes and other elements are typically used to aid this differentiation, as water from different sources shows different isotopic compositions.

See also GROUNDWATER.

meteorology Meteorology is the study of the Earth's atmosphere, along with its movements, energy, interactions with other systems, and weather forecasting. The main focus of meteorology is short-term weather patterns and data within a specific area, in contrast to climatology, which is the study of the average weather on longer timescales and often on a global basis. Different aspects of meteorology include the study of the structure of the atmosphere, such as its compositional and thermal layers, and how energy is distributed within these layers. It includes analysis of the composition of the atmosphere, how the relative and absolute abundance of elements have changed with time, and how different interactions of the atmosphere, biosphere, and lithosphere contribute to the atmosphere's chemical stability. A fundamental aspect of meteorology is relating how different factors, including energy from the Sun, contribute to cloud formation, movement of air masses, and weather patterns at specific locations. Meteorologists interpret these complex energy changes and moisture changes and try to predict the weather using this knowledge. Increasingly, meteorologists are able to use data collected from orbiting satellites to aid their interpretation of these complex phenomena. Satellites have immensely improved the ability to monitor and predict the strength and paths of severe storms, such as hurricanes, as well as monitor many aspects of the atmosphere, including moisture content, pollution, and wind patterns.

The Earth's atmosphere is rich in nitrogen and oxygen and has much lower abundances of water vapor, carbon dioxide, and other gases. Some gases, such as water vapor and carbon dioxide, have a tendency to trap heat in the atmosphere. Called greenhouse gases, such gases have varied in abundance throughout Earth history, causing large temperature changes of several to tens to even hundreds of degrees in the past 4.5 billion years.

The atmosphere is divided into several layers, including the lower troposphere (where most weather events take place), the stratosphere, the mesosphere, and finally the thermosphere, which is the hottest part of the atmosphere. The topmost layer of the atmosphere is called the exosphere, where many gas molecules escape from the gravitational pull of the Earth, and which grades into the highly charged ionosphere where many free electrons and ions exist.

Weather events in the atmosphere are driven by heat and energy transfer. Latent heat, the amount of energy in the form of heat that is absorbed or released by a substance during a change in state such as from a liquid to a solid, is an important source of atmospheric energy. Heat transfer by convection is also important in the atmosphere, as moving air transfers energy from one region to another. Radiation, or the transfer of energy by electromagnetic waves, is a third important source of energy in the atmosphere. The Sun emits energy as shortwave radiation that the Earth absorbs and subsequently emits as long wavelength infrared radiation. Water vapor and carbon dioxide can absorb energy at these wavelengths, warming the atmosphere. The atmosphere warms since it allows the Sun's short wavelength radiation through, but then traps the energy absorbed from the long wavelengths emitted from the Earth. The Earth then cools by radiation, which operates most efficiently on clear nights when the clouds do not trap the outgoing radiation.

Seasons on the Earth are caused by the Earth's tilt on its axis, which results in a seasonal variation in the amount of sunlight received in different hemispheres at different times of the year. Longer hours of more intense sunlight are associated with summer, and fewer hours of less intense sunlight are associated with winters in both hemispheres.

The daily variations in temperature in any place are controlled mainly by the balance between energy input from the Sun versus energy output by convection and radiation. With radiative cooling at night, the ground surface often cools more quickly than the overlying air, resulting in an inversion with the coldest air right next to the surface.

Water is an important element in the atmosphere. Absolute humidity is the density of water vapor in a given volume of air. Relative humidity is a measure of how close the air is to being saturated with water vapor, which also depends on temperature. The dew point is a measure of how much the air would have to be cooled for saturation to occur. When the air temperature and dew point are close the air feels much more humid and the relative humidity is high. Condensation occurs when the temperature reaches the dew point, and then small droplets of water form in the atmosphere or on surfaces, forming fog. If these small droplets of water freeze it produces small frozen droplets. Condensation above the surface produces clouds, which are classified according to their height and physical appearance and are commonly divided into high, middle, and low groups plus those that cut across many atmospheric levels.

Clouds tend to form horizontal layers in stable atmospheric conditions, but in unstable conditions parcels of air that get uplifted are warmer and lighter than surrounding air, so they continue to rise, forming large vertical clouds such as the towering cumulonimbus or thunderhead clouds. On warm days simple surface heating can cause cumulus clouds to form, at heights determined by the temperature and moisture content of the surface air. As droplets of moisture in clouds coalesce by moving in the convecting clouds and hitting each other, they gradually get large enough to form raindrops, or ice if the temperatures are low. Precipitation can have a variety of forms when it reaches the surface depending on the form it took in the cloud and on the near surface and surface temperatures. If the surface air is cold but the air aloft is warm, raindrops may fall and freeze on impact, a phenomenon called freezing rain. Snow can develop when both surface and higher level air is cold, and may fall as snowflakes, pellets, or grains. In situations where surface air is warm but cold air is aloft and there is a strong updraft (such as in a cumulonimbus cloud), hail stones may form in the cloud and hit the surface as balls of ice. Conditions in which there is warm air aloft and also on the ground cause precipitation to fall as rain.

Horizontal changes in temperature in the atmosphere produce areas with high and lower pressure. Plots of the height of equal air pressure show that low areas correspond to low pressure, and high areas to high pressure. The difference in the air pressure creates a force called the pressure gradient force that sets the air in motion in winds. This moving air is then acted on by the Coriolis force, which tends to move air to the right of its intended course in the Northern Hemisphere and to the left in the Southern Hemisphere. Winds in the Northern Hemisphere bend clockwise around high pressure and counterclockwise around low pressure centers. The Coriolis force causes the opposite pattern in the Southern Hemisphere.

There are many variations of microscale and mesoscale winds near the surface of the planet. The surface layer of air, extending to about half a mile (1 km) above the surface, is affected by surface friction, causing different types of winds to develop around different obstructions. Wind produces sand dunes and ripples in deserts and in snow fields and may deform vegetation near mountaintops where the winds are consistently strong. Mountains can produce strong rotations of the air downwind of the range, and frictional effects of fast-moving air aloft in jet streams can produce strong eddies in the surface layer, associated with strong turbulence. Local winds that blow uphill through mountain valleys during the day are called valley breezes, and those that flow downhill at night are called mountain breezes. Strong downslope winds are called katabatic winds. Larger scale mesocale wind systems often form near boundaries between the ocean and land, where differential heating of the land and water creates pressure differences that generate winds. Where winds blow across a large body of water, differential heating of the land and sea in different seasons may cause the winds to shift direction with the seasons, producing wind systems called monsoons.

There are many large-scale patterns of wind and pressure that persist around the world. Trade winds are those that blow toward the equator from the semipermanent high pressure zones located at 30° latitude. The trade winds from the Northern and Southern Hemispheres converge along the intertropical convergence zone. Poleward of the high pressure belts is a zone where the winds blow predominantly to the west (the westerlies). These meet a more poleward belt of east-flowing winds known as the easterlies along the polar front. Annual shifts in the positions of these belts produce the annual changes in patterns of precipitation that characterize many regions.

Jet streams form where strong winds aloft get concentrated into narrow bands, such as the polar jet stream that forms in response to temperature differences along the polar front, while subtropical jets form at high elevations above the subtropics along an upper level boundary called the subtropical front.

Interactions between the atmosphere and ocean are complex. Surface winds form ocean currents, and yet the oceans release energy that helps maintain atmospheric circulation. Atmospheric circulation patterns may change on seasonal or other timescales.

When warm air and water from the Austral-Indonesia region flows eastward toward South America it can form an El Niño, choking off the nutrient-rich upwelling and wreaking havoc on the environment and economics of South and Central America. The opposite effects, called La Niña, often dominate, and the alternating cycle of winds and currents is called the Southern Oscillation.

Air moves as coherent masses along boundaries called fronts. Stationary fronts have no movement, with cold air on one side and warm on the other. Winds usually blow parallel to fronts and in opposite directions on either side of the front. Fronts more typically move across continents and oceans, being driven by global atmospheric circulation. Leading edges of cold fronts are usually associated with showers as the cold air forces the warm air upward and replaces it, but in warm fronts the warm air rises over the colder surface air, producing cloudiness and widespread precipitation.

Mid-latitude cyclones form when an upper-level low-pressure trough forms west of a surface low-pressure area and when a shortwave disturbs this system, setting up surface and upper-level winds that enhance the development of the surface storm. The air converges at the surface level and rises in the center of the storm, forming precipitation. As the warm air rises and cool air sinks, energy is released, and the storm grows in strength as the potential energy is converted into kinetic energy. The storm may be steered by mid- or upper-level winds in the atmosphere.

Thunderstorms commonly develop when there is a humid layer of surface air, sunlight to heat the ground, and unstable air aloft. In these conditions the heated air may quickly rise, forming large cumulonimbus clouds that may drop locally heavy rains. When a strong vertical wind shear exists, severe thunderstorms may form. Supercells are large rotating thunderstorm systems that may persist for hours. Many thunderstorms form along frontal boundaries where cold air forces the warm air to rise, forming lines and clusters of storms called mesoscale convective complexes. Tornados, rapidly circulating columns of air that reach the ground, are often associated with supercells, and can have winds that reach a couple hundred miles per hour (few hundred km/hr) in the tornado core, typically less than several hundred yards (meters) wide.

Thunderhead cloud (cumulonimbus) rising *(Greg F. Riegler, Shutterstock, Inc.)*

Hurricanes are tropical cyclones with winds exceeding 74 miles per hour (119 km/hr) and include a well-organized mass of thunderstorms rotating about a central low pressure region in the storm's eye. Hurricanes form over warm tropical waters where surface winds converge along a tropical wave, initiating central airs to rise, forming a tropical depression. As the air continues to move into the storm system and rise in its center, much latent heat is released, causing more air to rise, and central pressures to reduce further, leading the storm to grow further. Energy is released by the storm in the cloud tops by radiational cooling so the strengthening of the storm depends on the balance between the energy gained by converting sensible and latent heat into kinetic energy in the storm eye and the energy lost in the cloud tops by radiation. Most hurricanes are steered to the west by the easterly winds in the tropics but may move westward when they move into mid-latitudes. Since the storms gain energy (and keep their energy balance) from the warm water, hurricanes rapidly lose strength when they move over cool water or land masses. Most damage from hurricanes is associated with the large storm surges that some generate, as well as the high winds and flooding rains.

See also ATMOSPHERE; CLIMATE; CLIMATE CHANGE; CLOUDS; EL NIÑO AND THE SOUTHERN OSCILLATION (ENSO); ENERGY IN THE EARTH SYSTEM; GREENHOUSE EFFECT; HURRICANES; MONSOONS, TRADE WINDS; PRECIPITATION; SUN; THERMODYNAMICS.

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Milankovitch, Milutin M. (1879–1958) Serbian *Mathematician, Physicist* Milutin Milankovitch was born and educated in Serbia, and was appointed to a chair in the University of Belgrade in 1909, where he taught courses in mathematics, physics, mechanics, and celestial mechanics. He is well known for his research on the relationship between celestial mechanics and climate on the Earth, and he is responsible for developing the idea that rotational wobbles and orbital deviations combine in cyclic ways to produce the climatic changes on the Earth. He determined how the amount of incoming solar radiation changes in response to several astronomical effects such as orbital tilt, eccentricity, and wobble. These changes in the amount of incoming solar radiation in response to changes in orbital variations occur with different frequencies, and produce cyclical variations known as Milankovitch cycles. Milankovitch's main scientific work was published by the Royal Academy of Serbia in 1941, during World War II in Europe. He calculated that the effects of orbital eccentricity, wobble, and tilt combine every 40,000 years to change the amount of incoming solar radiation, lowering temperatures and causing increased snowfall at high latitudes. His results have been widely used to interpret climatic variations, especially in the Pleistocene record of ice ages, and also in the older rock record.

See also CLIMATE CHANGE; MILANKOVITCH CYCLES.

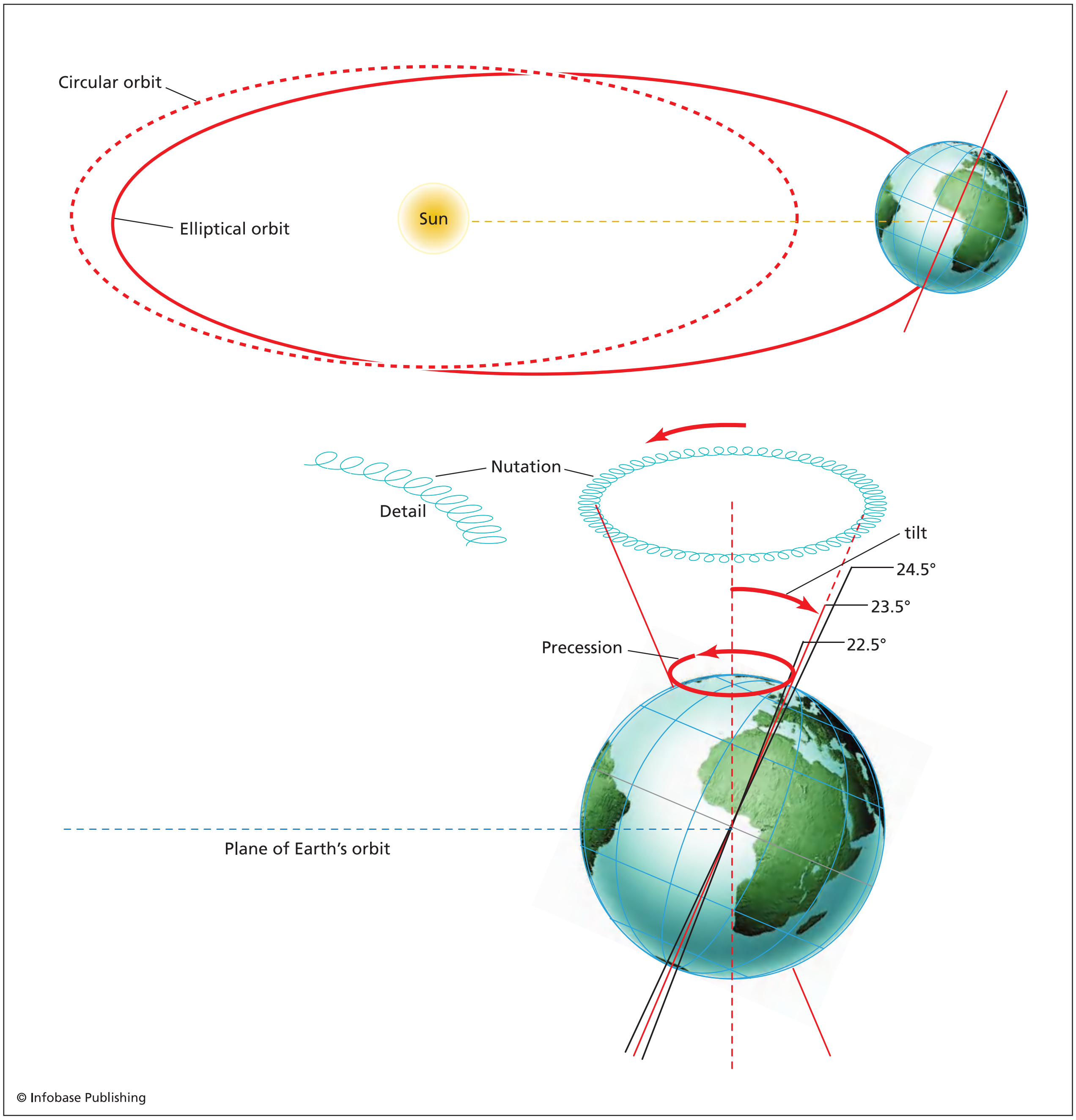
Milankovitch cycles Systematic changes in the amount of incoming solar radiation, caused by variations in Earth's orbital parameters around the Sun, are known as Milankovitch cycles. These changes can affect many Earth systems, causing glaciations, global warming, and changes in the patterns of climate and sedimentation.

Medium-term climate changes include those that alternate between warm and cold on time scales of 100,000 years or less. These medium-term climate changes include the semi-regular advance and retreat of the glaciers during the many individual ice ages in the past few million years. The last 2.8 million years have been marked by large global climate oscillations that have been recurring at approximately a 100,000-year periodicity at least for the past 800,000 years. The warm periods, called interglacial periods, appear to last approximately 15,000 to 20,000 years before regressing to a cold ice age climate. The last of these major glacial intervals began ending about 18,000 years ago, as the large continental ice sheets covering North America, Europe, and Asia began retreating. The main climate events related to the retreat of the glaciers, can be summarized as follows:

- 18,000 years ago: The climate begins to warm
- 15,000 years ago: Advance of glaciers halts and sea levels begin to rise
- 10,000 years ago: Ice Age megafauna goes extinct
- 8,000 years ago: Bering Strait land bridge becomes drowned, cutting off migration of people and animals.
- 6,000 years ago: The Holocene maximum warm period
- So far in the past 18,000 years, the Earth's temperature has risen approximately 16°F (10°C) and the sea level has risen 300 feet (91 m).

This past glacial retreat is but one of many in the past several million years, with an alternation of warm and cold periods apparently related to a 100,000 year periodicity in the amount of incoming solar radiation, causing the alternating warm and cold intervals. These systematic changes are known as Milankovitch cycles, after Milutin Milankovitch (1879–1958), a Serbian scientist who first clearly elucidated the relationships between the astronomical variations of the Earth orbiting the Sun and the climate cycles on Earth. Milankovitch's main scientific work was published by the Royal Academy of Serbia in 1941, during World War II in Europe. He was able to calculate that the effects of orbital eccentricity, wobble, and tilt combine every 40,000 years to change the amount of incoming solar radiation, lowering temperatures and causing increased snowfall at high latitudes. His results have been widely used to interpret the climatic variations, especially in the Pleistocene record of ice ages, and also in the older rock record.

Astronomical effects influence the amount of incoming solar radiation; minor variations in the path of the Earth in its orbit around the Sun and the inclination or tilt of its axis cause variations in the amount of solar energy reaching the top of the atmosphere. These variations are thought to be responsible for the advance and retreat of the Northern and Southern Hemisphere ice sheets in the past few million years. In the past two million years alone, the Earth



Orbital variations of the Earth cause changes in the amount of incoming solar radiation, known as Milankovitch cycles. Shown here are changes in the eccentricity of the orbit, the tilt of the spin axis (nutation), and precession of the equinoxes.

has seen the ice sheets advance and retreat approximately 20 times. The climate record as deduced from ice-core records from Greenland and isotopic tracer studies from deep ocean, lake, and cave sediments suggest that the ice builds up gradually over periods of about 100,000 years, then retreats rapidly over a period of decades to a few thousand years. These patterns result from the cumulative effects of different astronomical phenomena.

Several movements are involved in changing the amount of incoming solar radiation. The Earth rotates around the Sun following an elliptical orbit, and the shape of this elliptical orbit is known as its eccentricity. The eccentricity changes cyclically with time with a period of 100,000 years, alternately bringing the Earth closer to and farther from the Sun in summer and winter. This 100,000-year cycle is about the same as the general pattern of glaciers advancing and retreating every 100,000 years in the past two million years, suggesting that this is the main cause of variations within the present-day ice age. Presently, the Earth is in a period of low eccentricity (~3 percent) and this yields a seasonal change in solar energy of ~7 percent. When the eccentricity is at its peak (~9 percent), "seasonality" reaches ~20 percent. In addition a more eccentric orbit changes the length of seasons in each hemisphere by changing the length of time between the vernal and autumnal equinoxes.

The Earth's axis is presently tilting by 23.5°N/S away from the orbital plane, and the tilt varies between 21.5°N/S and 24.5°N/S. The tilt, also known as obliquity, changes by plus or minus 1.5°N/S from a tilt of 23°N/S every 41,000 years. When the tilt is greater, there is greater seasonal variation in temperature. For small tilts, the winters would tend to be milder and the summers cooler. This would lead to more glaciation.

Wobble of the rotation axis describes a motion much like a top rapidly spinning and rotating with a wobbling motion, such that the direction of tilt toward or away from the Sun changes, even though the tilt amount stays the same. This wobbling phenomenon is known as precession of the equinoxes, and it has the effect of placing different hemispheres closest to the Sun in different seasons. This precession changes with a double cycle, with periodicities of 23,000 years and 19,000 years. Presently the precession of the equinoxes is such that the Earth is closest to the Sun during the Northern Hemisphere winter. Due to precession, the reverse will be true in ~11,000 years. This will give the Northern Hemisphere more severe winters.

Because each of these astronomical factors acts on a different time scale, they interact in a complicated way, known as Milankovitch cycles. Using the power of understanding these cycles, we can make predictions of where the Earth's climate is heading, whether we are heading into a warming or cooling period and whether we need to plan for sea level rise, desertification, glaciation, sea level drops, floods, or droughts. When all the Milankovitch cycles (alone) are taken into account, the present trend should be toward a cooler climate in the Northern Hemisphere, with extensive glaciation. The Milankovitch cycles may help explain the advance and retreat of ice over periods of 10,000 to 100,000 years. They do not explain what caused the Ice Age in the first place.

Western aspect of the Pelmo massif in the Italian Dolomite Mountains. The cyclical layering recorded by the beds (horizontal) is interpreted as records of Milankovitch climate cycles. *(Gillian Price/Alamy)*

The pattern of climate cycles predicted by Milankovitch cycles is made more complex by other factors that change the climate of the Earth. These include changes in thermohaline circulation, changes in the amount of dust in the atmosphere, changes caused by reflectivity of ice sheets, changes in concentration of greenhouse gases, changing characteristics of clouds, and even the glacial rebound of land that was depressed below sea level by the weight of glaciers.

Milankovitch cycles have been invoked to explain the rhythmic repetitions of layers in some sedimentary rock sequences. The cyclical orbital variations cause cyclical climate variations, which in turn are reflected in the cyclical deposition of specific types of sedimentary layers in sensitive environments. There are numerous examples of sedimentary sequences where stratigraphic and age control are sufficient to be able to detect cyclical variation on the time scales of Milankovitch cycles, and studies of these layers have proven consistent with a control of sedimentation by the planet's orbital variations. Some examples of Milankovitch-forced sedimentation have been documented from the Dolomite Mountains of Italy, the Proterozoic Rocknest Formation of northern Canada, and from numerous coral reef environments.

Predicting the future climate on Earth involves very complex calculations, including inputs from the long- and medium-term effects described in this entry, and some short-term effects such as sudden changes caused by human inputs of greenhouse gases to the atmosphere, and effects such as unpredicted volcanic eruptions. Nonetheless, most climate experts expect that the planet will continue to warm on the hundreds-of-years time scale. However, based on the recent geological past, it seems reasonable that the planet could be suddenly plunged into another ice age, perhaps initiated by sudden changes in ocean circulation, following a period of warming. Climate is one of the major drivers of mass extinction, so the question remains if the human race will be able to cope with rapidly fluctuating temperatures, dramatic changes in sea level, and enormous shifts in climate and agriculture belts.

See also CLIMATE CHANGE; MILANKOVITCH, MILUTIN M.; SEQUENCE STRATIGRAPHY; STRATIGRAPHY, STRATIFICATION, CYCLOTHEM.

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mineral, mineralogy The branch of geology that deals with the classification and properties of minerals is closely related to petrology, the branch of geology that deals with the occurrence, origin, and history of rocks. Minerals are the basic building blocks of rocks, soil, and sand. Most beaches are made of the mineral quartz, which is very resistant to weathering and erosion by the waves. Most minerals, like quartz or mica, are abundant and common, although some minerals like diamonds, rubies, sapphires, gold, and silver are rare and very valuable. Minerals contain information about the chemical and physical conditions in the regions of the Earth that they formed in. They can often help discriminate which tectonic environment a given rock formed in, and they can tell us information about the inaccessible portions of Earth. For example, mineral equilibrium studies on small inclusions in diamonds show that they must form below a depth of 90 miles (145 km). Economies of whole nations are based on exploitation of mineral wealth; for instance, South Africa is such a rich nation because of its abundant gold and diamond mineral resources.

The two most important characteristics of minerals are their composition and structure. The composition of minerals describes the kinds of chemical elements present and their proportions, whereas the structure of minerals describes the way in which the atoms of the chemical elements are packed together.

Mineralogists have identified nearly 4,000 minerals, most made out of the eight most common mineral-forming elements. These eight elements, listed in the table "The Eight Most Common Mineral-Forming Elements," make up greater than 98 percent of the mass of the continental crust. Most of the other 133 scarce elements do not occur by themselves, but occur with other elements in compounds by ionic substitution. For example, olivine may contain trace amounts of copper (Cu), nickel (Ni), cobalt (Co), manganese (Mn), and other elements.

The two elements oxygen and silicon make up more than 75 percent of the crust, with oxygen alone forming nearly half of the mass of the continental crust. Oxygen forms a simple anion (O^{2-}), and silicon forms a simple cation (Si^{4+}). Silicon and oxygen combine together to form a very stable complex anion that is the most important building block for minerals—the silicate anion $(SiO_4)^{4-}$. Minerals that contain this anion are known as the silicate minerals, and they are the most common naturally occurring inorganic compounds in the solar system. The other, less common building blocks of minerals (anions) are oxides (O^{2-}), sulfides (S^{2-}), chlorides (Cl^-), carbonates $(CO_3)^{2-}$, sulfates $(SO_4)^{2-}$, and phosphates $(PO_4)^{3-}$.

Minerals are classified into eight major groups based on the main type of cation present in the mineral structure, a classification scheme championed by James Dana in the early 1800s. His classification recognized (1) native elements; (2) sulfides; (3) oxides and hydroxides; (4) halides; (5) carbonates, nitrates, borates, and iodates; (6) sulfates, chromates, molybdates, and tungstates; (7) phosphates, arsenates, and vanadates; and (8) silicates.

Eight types of minerals: sulfur, sapphire, orpiment/realgar, cinnabar, malachite, olivine (peridot), copper, and beryl *(Charles D. Winters/Photo Researchers, Inc.)*

THE EIGHT MOST COMMON MINERAL-FORMING ELEMENTS

Element	Abbreviation	Percentage of Continental Crust Mass
Oxygen	O	46.6
Silicon	Si	27.7
Aluminum	Al	8.1
Iron	Fe	5.0
Calcium	Ca	3.6
Sodium	Na	2.8
Potassium	K	2.6
Magnesium	Mg	2.1

Approximately 20 minerals are so common that they account for greater than 95 percent of all the minerals in the continental and oceanic crust; these are called the rock-forming minerals. Most rock-forming minerals are silicates and they have some common features in the way their atoms are arranged.

THE SILICATE TETRAHEDRON

The silicate anion is made of four large oxygen atoms and one small silicon atom that pack themselves together to occupy the smallest possible space. This shape, with big oxygen atoms at four corners of the structure and the silicon atom at the center, is known as the silicate tetrahedron. Each silicate tetrahedron has four unsatisfied negative charges (Si has a charge of +4, whereas each oxygen has a charge of -2). To make a stable compound the silicate tetrahedron must therefore combine to neutralize this extra charge, which can happen in one of two ways:

(1) Oxygen can form bonds with cations (positively charged ions). For instance, Mg^{2+} has a charge of +2, and by combining with

Mg^{2+}, the silicate tetrahedron makes a mineral called olivine $(Mg_2)SiO_4$.

(2) Two adjacent tetrahedra can share an oxygen atom, making a complex anion with the formula $(Si_2O_7)^{6-}$. This process commonly forms long chains, so that the charge is balanced except at the ends of the structure. This process of linking silicate tetrahedra into large anion groups is called polymerization, and it is the most common way to build minerals, but in making the various possible combinations of tetrahedra, one rule must be followed, that is tetrahedra can only be linked at their apexes.

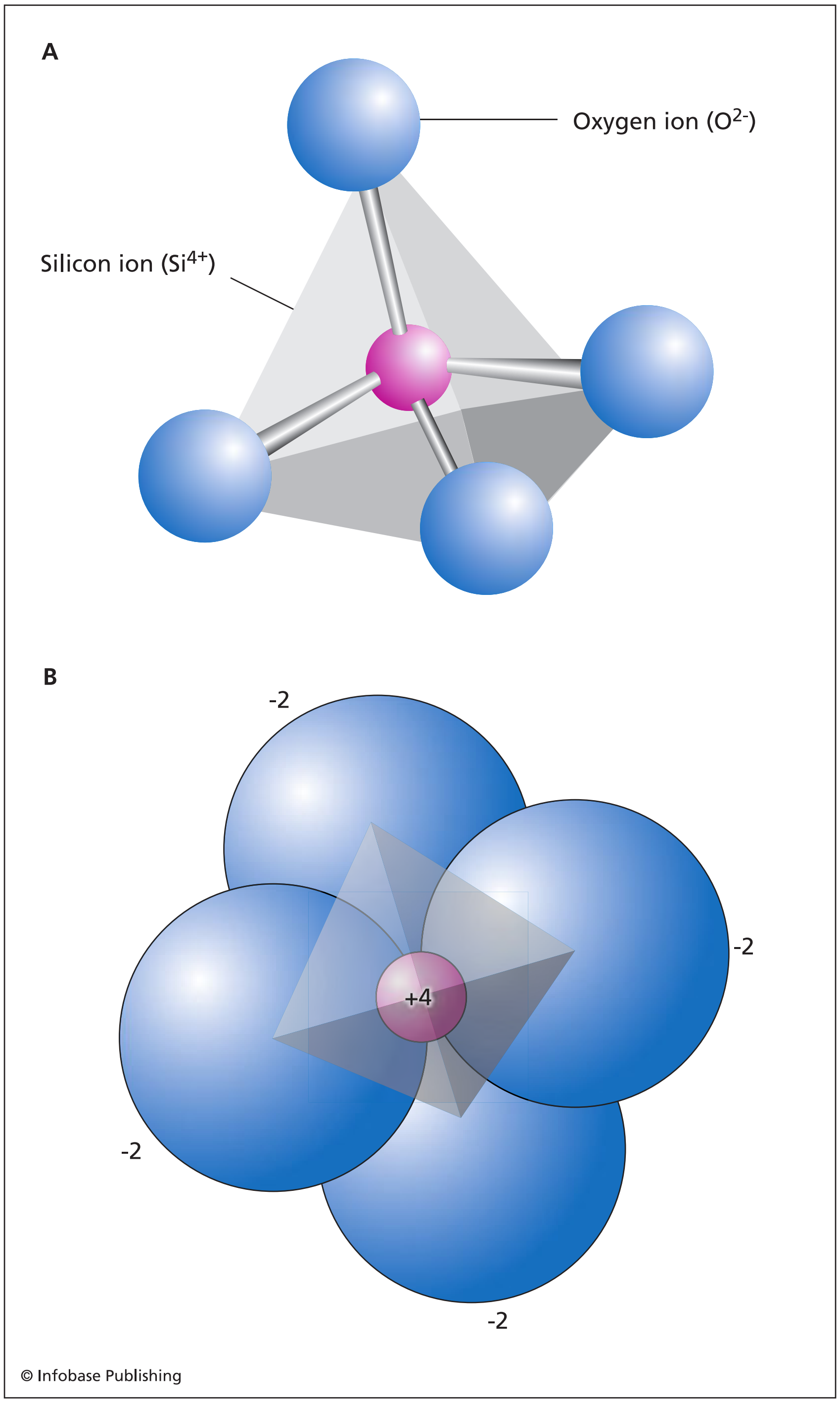

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Diagram showing silicate tetrahedra

Olivine is one of the most important minerals on Earth, forming much of the oceanic crust and upper mantle. It has the formula $(Mg,Fe)_2SiO_4$ and forms the gem peridot.

Garnet is made of isolated silicate tetrahedra packed together without polymerizing with other tetrahedra. There are many different kinds of garnets, with almandine being one of the more common, deep red varieties that forms a common gemstone. Ionic substitution is common, with garnet having the chemical formula $A_3B_2(SiO_4)^{3}$, where:

$A = Mg^{2+}, Fe^{2+}, Ca^{2+}, Mn^{2+}$

$B = Al^{3+}, Fe^{3+}$

Pyroxene and amphibole both contain continuous chains of silicate tetrahedra. Polymerized chains of tetrahedra form pyroxenes, whereas amphiboles are built in double chains or linked rings. In both of these structures, the chains are bound together by cations such as Ca^{2+}, Mg^{2+}, and Fe^{2+}, which satisfy the negative charges of the polymerized tetrahedra. Pyroxenes are very common minerals in the oceanic crust and mantle and also occur in the continental crust. Amphiboles are very common in metamorphic rocks, have a complicated chemical formula, and can hold a large variety of cations in their crystal structure.

Clays, micas, and chlorites are all closely related to sheet silicates, made of polymerized sheets of tetrahedra. By sharing three oxygen atoms with adjacent tetrahedra, each tetrahedron has only one oxygen atom remaining unbalanced, and it is typically balanced by Al^{3+} cations, which occupy spaces between the sheets. The sheet structure is why micas are easy to peel apart on cellophane-like surfaces.

Quartz, one of the most common minerals, also has one of the most common polymerizations. Its charges are satisfied by sharing all of its oxygen in a three-dimensional network. Quartz typically has six-sided crystals and has many other different forms and colors.

Feldspars are the most common minerals in the Earth's crust. They account for 60 percent of all minerals in the continental crust and 75 percent of the volume. Feldspars are also common in the oceanic crust. Like quartz, feldspars have a structure formed by polymerization of all the oxygen atoms, and some of the silicon atoms are replaced by Al^{3+}. Many different kinds of feldspar minerals form by the addition of different cations to the structure. For instance, potassium feldspar has the formula $K(Si_3Al)O_8$, albite has the formula $Na(Si_3Al)O_8$, and anorthite has the formula $Ca(Si_2Al_2)O_8$. A complete range of chemical compositions of feldspars is possible between the albite and anorthite varieties. These feldspar minerals are known as the plagioclase feldspars.

Silicates are the most abundant rock-forming minerals, but other types do occur in sufficient quantities to call them rock-forming minerals. Oxides use the oxygen anion and include ore minerals such as chromium, uranium, tin, and magnetite (FeO_4). Sulfides are minerals such as pyrite, copper, lead, zinc, cobalt, mercury, or silver that combine with the sulfur anion. For instance, FeS_2 is the formula for pyrite, commonly known as fool's gold. The carbonates calcite, aragonite, and dolomite form with the complex carbonate anion $(CO_3)^{2-}$. Phosphates are formed using the complex anion $(PO_4)^{3-}$. An example is the mineral apatite, used for fertilizers, and the same substance as that which forms teeth and bones. Sulfate minerals are formed using the complex sulfate ion $(SO_4)^{2-}$. Gypsum and anhydrite, sulfate minerals formed by evaporation of salt water, are commonly used to make plaster.

Uncut emerald from Colombia *(Carl Frank/Photo Researchers, Inc.)*

One of the most important nonsilicate mineral groups is the carbonates, which are built using the carbonate ion. The most common carbonates are calcite ($CaCO_3$) and dolomite ($(Ca,MgCO_3)_2$). These minerals are common in sedimentary rock sequences deposited under marine conditions. Other nonsilicate minerals common in sedimentary rocks include the halide mineral halite (NaCl) and the sulfate gypsum ($CaSO_4$), both common in evaporate sequences formed when ocean waters evaporate and leave the dissolved minerals behind as sedimentary layers.

Native elements are not as common as many other mineral groups, and consist of free-occurring elements such as gold (Au), copper (Cu), silver (Ag), platinum (Pt), diamond (C), and graphite (C). Non-native-element economically important minerals include some oxides (hematite, magnetite, chromite, and ilmenite) and sulfides such as pyrite, chalcopyrite, galena, and sphalerite.

THE PROPERTIES OF MINERALS

Minerals have specific properties determined by their chemistry and crystal structure. Certain properties are characteristic of certain minerals, and one can identify minerals by learning these properties. The most common properties are crystal form, color, hardness, luster, cleavage, specific gravity, and taste.

When a mineral grows freely, it forms a characteristic geometric solid bounded by geometrically arranged plane surfaces (this is the crystal form). This symmetry is an external expression of the symmetric internal arrangement of atoms, such as in repeating tetrahedron arrays. Individual crystals of the same mineral may look somewhat different because the relative sizes of individual faces may vary, but the angles between faces are constant and diagnostic for each mineral.

Every mineral has a characteristic crystal form. Some minerals have such distinctive forms that they can be readily identified without measuring angles between crystal faces. For instance, pyrite is recognized as interlocking growth of cubes, whereas asbestos forms long silky fibers. These distinctive characteristics are known as growth habit.

Cleavage is the tendency of a mineral to break in preferred directions along bright reflective planar surfaces. External structure deters the planar surface along which cleavage occurs; cleavage occurs along planes where the bands between the atoms are relatively weak.

Luster is the quality and intensity of light reflected from a mineral. Typical lusters include metallic (like a polished metal), vitreous (like a polished glass),

MOH'S HARDNESS SCALE

10	Diamond
9	Corundum (ruby, sapphire)
8	Topaz
7	Quartz
6	Potassium feldspar (pocketknife, glass)
5	Apatite (teeth, bones)
4	Fluoride
3	Calcite (copper penny)
2	Gypsum (fingernail)
1	Talc

resinous (like resin), pearly (like a pearl), and greasy (oily).

Color is not reliable for identification of minerals, since it is typically determined by ionic substitution. For instance, sapphire and rubies are both varieties of the mineral corundum, but with different types of ionic substitution. However, the color of the streak a mineral leaves on a porcelain plate is often diagnostic for opaque minerals with metallic lusters.

The density of a mineral is a measure of mass per unit volume (g/cm^3). Density describes "how heavy the mineral feels." Specific gravity is an indirect measure of density; it is the ratio of weight of a substance to the weight of an equal volume of water (specific gravity has no units because it is a ratio).

Hardness is a measure of the mineral's relative resistance to scratching, as listed in the table "Moh's Hardness Scale." Hardness is governed by the strength of bonds between atoms and is very distinctive and useful for mineral identification. A mineral's hardness can be determined by the ease with which one mineral can scratch another. For instance, talc (used for talcum powder) is the softest mineral, whereas diamond is the hardest mineral.

See also crystal, crystal dislocations; Dana, James Dwight; economic geology; geochemistry; petrology and petrography; thermodynamics.

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monsoons, trade winds A wind system that changes direction with the seasons is known as a monsoon, after the Arabic term *mausim*, meaning seasons. The Arabian Sea is characterized by monsoons, with the wind blowing from the northeast for six months, then from the southeast for the other half of the year. Seasonal reversal of winds is probably best known from India and southern Asia, where monsoons bring seasonal rains and floods.

In contrast to monsoons, trade winds are steady winds that blow between 0° and 30° latitude, from the northeast to southwest in the Northern Hemisphere and from southeast to northwest in the Southern Hemisphere. The trade winds are formed as the cool air from Hadley cell circulation returns to the surface at about 15–30° latitude, and then returns to the equatorial region. The Coriolis force deflects the moving air to the right in the Northern Hemisphere, causing the air to flow from northeast to southwest, and to the left in the Southern Hemisphere, causing a southeast to northwest flow. They are named trade winds because sailors used the reliability of the winds to aid their travels from Europe to the Americas. The doldrums, an area characterized by weak stagnant air currents, bound the trade winds, on high latitudes by the horse latitudes, characterized by weak winds, and toward the equator. The origin of the term *horse latitudes* is uncertain, but legend has it that it comes from ships traveling to the Americas that became stranded by the lack of winds in these regions, and were forced to kill onboard horses to conserve fresh water supplies and to eat their meat.

The Asian and Indian monsoon originates from differential heating of the air over the continent and ocean with the seasons. In the winter monsoon, the air over the continents becomes much cooler than the air over the ocean, and a large, shallow, high-pressure system develops over Siberia. This produces a clockwise rotation of air that rotates over the South China Sea and Indian Ocean, producing northeasterly winds and fair weather with clear skies over eastern and southern Asia. In contrast, in the summer monsoon, the air pattern reverses itself as the air over the continents becomes warmer than the air over the oceans. This produces a shallow, low-pressure system over the Indian subcontinent, within which the air rises. Air from the Indian Ocean and Arabian Sea rotates counterclockwise into the low-pressure area, bringing moisture-laden winds into the subcontinent. As the air rises due to convergence and orographic (mountain) effects, it cools below its saturation point, resulting in heavy rains and thunderstorms that characterize the summer monsoon of India from June through September. Some regions of India, especially the Cherrapunji area in the Khasi Hills of northeastern India, receive more than 40 inches (1,000 cm) of rain during a summer monsoon. A similar pattern develops over Southeast Asia. Other less intense monsoons are known from Australia, South America, Africa, and parts of the desert southwest, Pacific coast, and Mississippi Valley of the United States.

The strength of the Indian monsoon is related to the El Niño-Southern Oscillation. During the El Niño events, surface water near the equator in the central and eastern Pacific is warmer than normal, forming excessive rising air, thunderstorms, and rains in this region. This pattern causes air to sink over eastern Asia and India, leading to a summer monsoon with much lower than normal rainfall totals.

See also ATMOSPHERE; CLIMATE; CLIMATE CHANGE; EL NIÑO AND THE SOUTHERN OSCILLATION (ENSO); ENERGY IN THE EARTH SYSTEM.

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N

Neogene The Neogene is the second of three periods of the Cenozoic, including the Paleogene, Neogene, and Quaternary, and the second of two subperiods of the Tertiary, younger than Paleogene. Its base is at 23.8 million years ago and its top is at 1.8 million years ago, followed by the Quaternary period. Charles Lyell proposed the subdivision of the Neogene into the Miocene, Pliocene, Pleistocene, and Recent epochs in his book *Principles of Geology* in 1833. Austrian geologist Moriz Hörnes formally proposed the currently accepted division of the Neogene in 1835 and included only the older parts of Lyell's Neogene.

The Atlantic and Indian Oceans were open in the Neogene, and the Earth's plate mosaic resembled the modern configuration. The collision of India with Asia was well under way, and Australia had already rifted and was moving away from Antarctica, isolating Australia and leading to the development of the cold circumpolar current and the Antarctic ice cap. Subduction and accretion events were active along the Cordilleran margins of North and South America. Basin-and-range extension was active, and the Columbia River basalts were erupted in the northwestern United States. The San Andreas fault developed in California during subduction of the East Pacific Rise.

One of the more unusual events to mark the Neogene is the development of up to 1.2 miles (2 km) of salt deposits between 5.5 and 5.3 million years ago in the Mediterranean region. This event, known as the Messinian salt crisis, was caused by the isolation of the Mediterranean Sea by collisional tectonics and falling sea levels that caused the sea to at least partially evaporate several times during the 200,000-year-long crisis. Rising sea levels ended the Messinian crisis 5.3 million years ago, when waters of the Atlantic rose over the natural dam in the Strait of Gibraltar, probably forming a spectacular waterfall.

A meteorite impact event occurred about 15 million years ago, forming the 15-mile- (24-km-) wide Ries Crater near Nordlingen, Germany. The meteorite that hit the Earth in this event is estimated to have been half a mile (1 km) in diameter, releasing the equivalent of a 100,000 megaton explosion. About 55 cubic feet (155 m^3) of material was displaced from the crater, some of which formed fields of tektites, unusually shaped melted rock that flew through the air for up to 248.5 miles (400 km) from the crater.

The Neogene saw the spread of grasses and weedy plants across the continents and the development of modern vertebrates. Snakes, birds, frogs, and rats expanded their niches, whereas the marine invertebrates experienced few changes. Humans evolved from earlier apelike hominids. Continental glaciations in the Northern Hemisphere began in the Neogene, and continue to this day.

See also Cenozoic; Tertiary.

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Neolithic *Neolithic* is an archaeological term for the last division of the Stone Age, during which time humans developed agriculture and domesticated animals. The transition from hunter-gatherer and nomadic types of existence to the development of farming took place about 10,000–8,000 years ago in the Fertile Crescent, a broad stretch of land that extends from southern Israel through Lebanon, western Syria, Turkey, and through the Tigris-Euphrates Valley of Iraq and Iran. The Neolithic revolution and the development of stable agricultural practices led to an unprecedented explosion of the human population that continues to this day. About a million years ago, an estimated few thousand humans migrated on the Earth, and by about 10 thousand years ago this number had increased only to a mere 5–10 million. When humans began stable agricultural practices and domesticated some species of animals, the population rate increased substantially. The increased standards of living and nutrition caused the population growth to soar to about 20 million by 2,000 years ago, and 100 million by 1,000 years ago. By the 18th century, humans manipulated their environments to a greater degree, began public health services, and recognized and sought treatments for diseases that previously claimed many lives. The average life span soared, and world population surpassed 1 billion in the year

Map of the Fertile Crescent stretching from the Levant (Israel and Lebanon) through rolling hills in parts of Syria, southern Turkey, Iraq, and Iran. Ancient cities and agriculture arose in this area, with many early cities located in the Sumerian region between the Tigris and Euphrates Rivers, in what is now southern Iraq.

1810. A mere 100 years later, the world population doubled again to 2 billion, and had reached 4 billion by 1974. World population is now close to 7 billion and climbing more rapidly than at any time in history, doubling every 50 years.

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Neptune The eighth and farthest planet from the center of the solar system, the giant Jovian planet Neptune orbits the Sun at a distance of 2.5 billion miles (4.1 billion km, or 30.1 astronomical units), completing each circuit every 165 years. Rotating about its axis every 16 hours, Neptune has a diameter of 31,400 miles (50,530 km) and a mass of more than 17.21 times that of Earth. Its density of 1.7 grams per cubic centimeter shows that the planet has a dense rocky core surrounded by metallic, molecular, and gaseous hydrogen, helium, and methane, giving the planet its blue color.

Neptune is unusual in that it generates its own heat, radiating 2.7 times more heat than it receives from the Sun. The source of this heat is uncertain, but it may be heat trapped from the planet's formation that is only slowly being released by the dense atmosphere. The cloud systems that trap this heat are visible from Earth-based telescopes and include some large hurricane-like storms such as the former Great Dark Spot, a storm about the size of the Earth, similar in many ways to the Great Red Spot on Jupiter, but that has dissipated.

Neptune has two large moons visible from Earth, Triton and Nereid, and six other smaller moons discovered by the *Voyager 2* spacecraft. Triton has a diameter of 1,740 miles (2,800 km) and orbits Neptune at a distance of 220,000 miles (354,000 km) from the planet. It is the only large moon in the solar system that has a retrograde orbit.

See also EARTH; JUPITER; MARS; MERCURY; SATURN; SOLAR SYSTEM; URANUS; VENUS.

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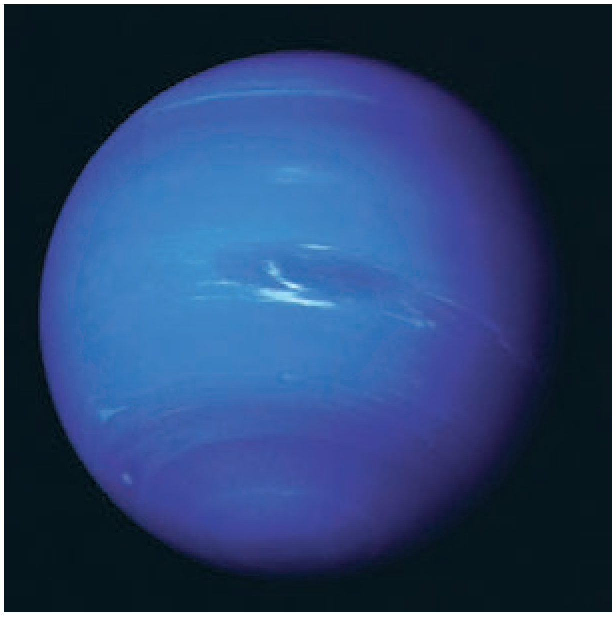


Neptune and swirling clouds. Neptune's blue-green atmosphere is shown in greater detail than ever before by the *Voyager 2* spacecraft as the craft rapidly approaches its encounter with the giant planet. This color image, produced from a distance of about 10 million miles (16 million km), shows several complex and puzzling atmospheric features. The Great Dark Spot (GDS) seen at the center is about 8,080 miles (l3,000 km) by 4,100 miles (6,600 km) in size—as large along its longer dimension as the Earth. The bright, wispy "cirrus-type" clouds seen hovering in the vicinity of the GDS are higher in altitude than the dark material of unknown origin that defines its boundaries. A thin veil often fills part of the GDS interior, as seen on the image. The bright cloud at the southern (lower) edge of the GDS measures about 600 miles (l,000 km) in its north-south extent. The small, bright cloud below the GDS, dubbed the "scooter," rotates faster than the GDS, gaining about 30 degrees eastward (toward the right) in longitude every rotation. Bright streaks of cloud at the latitude of the GDS, the small clouds overlying it, and a dimly visible dark protrusion at its western end are examples of dynamic weather patterns on Neptune, which can change significantly on timescales of one rotation (about 16 hours). *(NASA Jet Propulsion Laboratory (NASA-JPL)*

North American geology The North American continent contains the oldest rocks known on the planet, and its core is made of a complex amalgam of some of the oldest Archean cratons on Earth. These cratons formed in complex accretionary orogenic events and then were brought together to form the cratonic core of North America in a series of collisional events in the Proterozoic. Embryonic North America formed an integral part of the supercontinents—Pangaea, and the progressively older Gondwana (1.0–0.54 billion years ago), Rodinia (1.6–1.0 billion years ago), Nuna (2.5–1.6 billion years ago), and Kenoraland (Archean)—and is the largest preserved fragment in the world of a continent assembled in the Proterozoic. Following the amalgamation of these continental blocks in the core of the continent, North America continued to evolve and grow by accretion and collision of exotic arc and other terranes in the Appalachian/Caledonian, Cordilleran, and Franklinian orogens. Understanding how the North American continent formed is instructive to understanding processes in continental formation and growth worldwide.

CRATONIC CORE OF NORTH AMERICA

There are four main Archean cratons that form the oldest core of North America. These are the Slave, Superior, Churchill, and Wyoming cratons. Each of these is reviewed briefly below, then their assembly together in the Proterozoic is discussed.

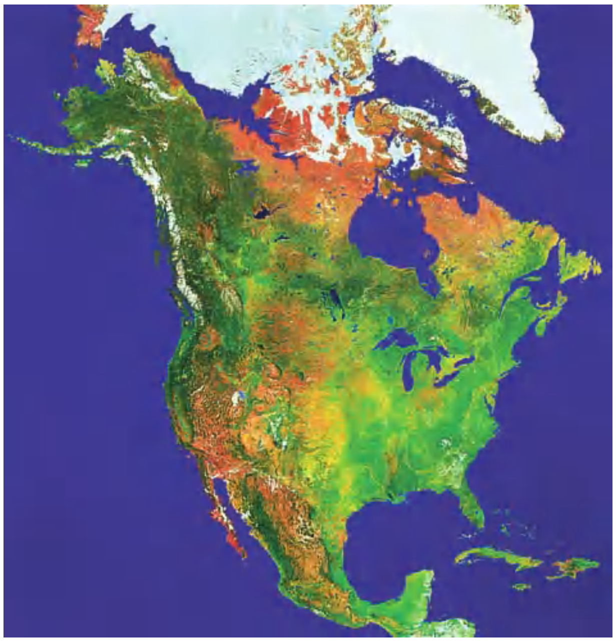
Slave Craton

The Slave craton is an Archean granite-greenstone terrane located in the northwestern part of the Canadian shield. The Archean history of the craton spans the interval from 4.03 billion years ago, the age of the world's oldest rocks, known as the Acasta Gneisses exposed in a basement culmination in the Wopmay orogen, to 2.6–2.5 billion years ago, the age of major granitic plutonism throughout the province. The margins of the craton were deformed and loaded by sediments during Proterozoic orogenies, and the craton is cut by several Proterozoic mafic dike swarms.

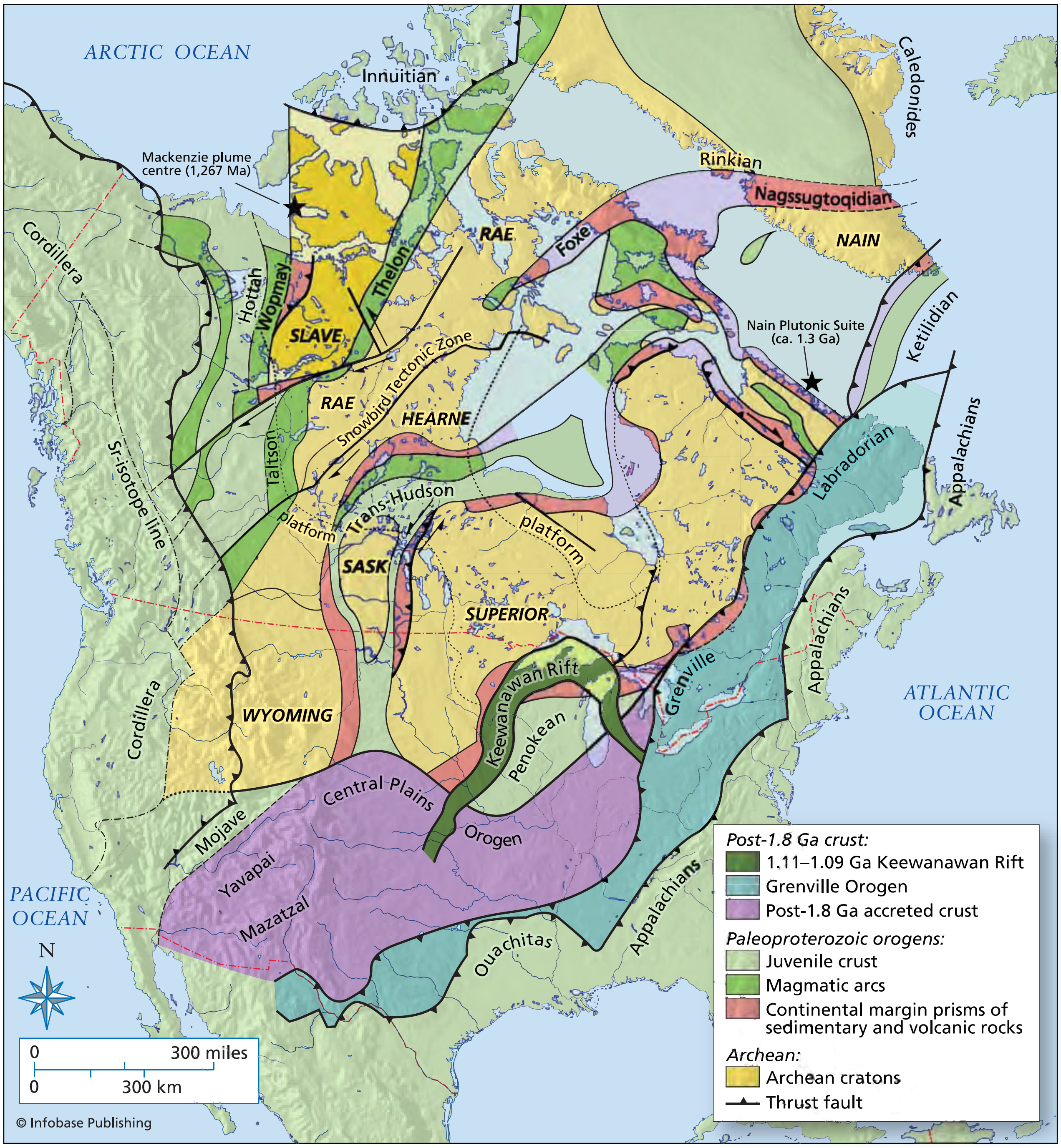
Most of the volcanic and sedimentary rocks of the Slave craton were formed in the interval between 2.7 and 2.65 billion years ago. Syntectonic to posttectonic plutons form about half of the map area of the province. The geology of the Slave Province shows some broad-scale tectonic zonations if the late granites are ignored. Greenstone belts are concentrated in a narrow northerly trending swath in the central part of the province, and the relative abundance of mafic volcanics, felsic volcanics, clastic rocks, and gneisses is different on either side of this line. The dividing line is coincident with a major Bouger gravity anomaly and with an isotopic anomaly indicating that older crust was involved in granitoid petrogenesis in the west, but not in the east. Greenstone belts west of the line comprise predominantly mafic volcanic and plutonic rocks, whereas volcanic belts to the east contain a much larger percentage of intermediate and felsic volcanic material. This is most evident in a large belt of northwest-trending felsic volcanics extending from south and east of Bathurst Inlet toward Artillery Lake. Quartzofeldspathic gneisses older than the greenstones are rare throughout the province and are confined to a line west of the central dividing line.

In the middle 1980s, American geologist T. M. Kusky proposed that these major differences in geology across the Slave Province reflect that it is divided into a number of different tectonic terranes. These ideas were initially debated but later largely accepted and modified by further mapping, seismic surveys, and geochemical analysis. An older gneissic terrane in the west, known as the Anton terrane, contains the world's oldest known rocks and is overlain by a platform-type sedimentary sequence. The Contwoyto terrane and Hackett River arc represent an accretionary prism and island arc that accreted to the Anton terrane in the late Archean, uplifting the Sleepy Dragon terrane in a basement culmination.

Gneissic rocks of the Anton terrane extend from Yellowknife to the Anialik River. The name is taken from the Anton complex exposed north of Yellowknife, which consists of metamorphosed granodiorite to quartz diorite, intruded by younger granitoids. The Anton terrane dips under the Wopmay orogen in the west, and its eastern contact is marked by a several-kilometer-thick, nearly vertical mylonite zone, best exposed in the vicinity of Point Lake. The Anton terrane includes the oldest rocks known in

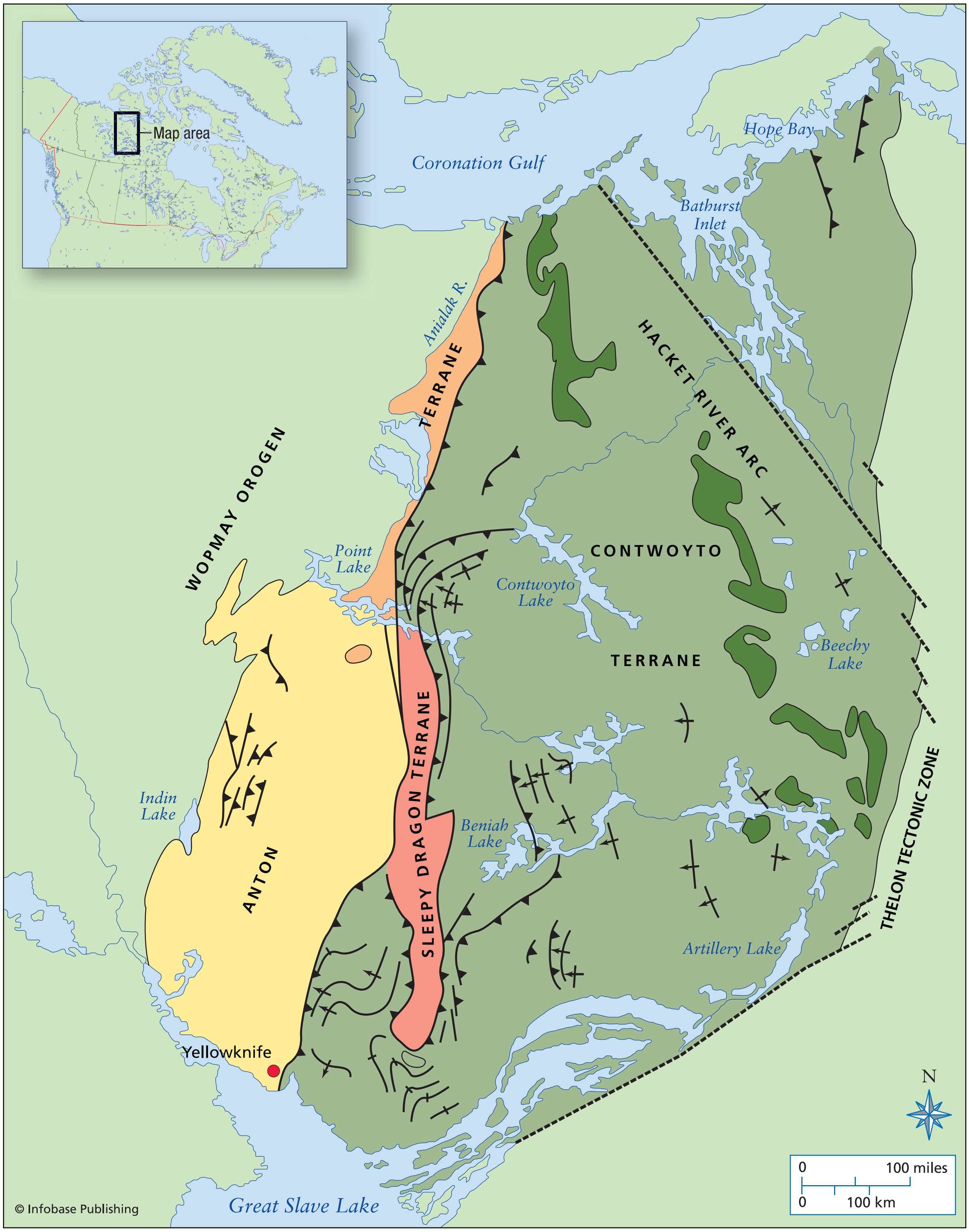


Landsat satellite mosaic of North America *(WorldSat International Inc./Photo Researchers, Inc.)*



Tectonic province map of North America showing Archean cratons, including the Superior, Slave, and Wyoming Provinces, Paleoproterozoic orogens, Neoproterozoic orogens, including the Grenville orogen, and Phanerozoic orogens, including the Appalachians and Cordilleran belts *(Map inspired by Paul Hoffman)*

the world, the 4.03 billion-year-old Acasta gneisses exposed in a basement culmination along the border with the Wopmay orogen (slightly older rocks have recently been suggested to be present in Labrador, but their age is debated and the uncertainties on the dating methods are large). Also, 3.48 to 3.21 billion-year-old tonalitic gray gneisses are exposed in several locations, and similar undated old gray gneissic rocks are preserved as inclusions and small outcrop belts within a sea of younger granites in the western part of the craton. Several different types of gneissic rocks are present in these areas, including a variety of metamorphosed igneous and sedimentary rocks. The oldest type of gneiss recognized in most places includes tonalitic to granodioritic layers with mafic amphibolite bands that are probably deformed dikes. Younger orthogneisses have tonalitic, granodioritic, and dioritic protoliths, and migmatization is common. Locally, especially near the eastern side of the Anton terrane, the older gneisses are overlain by a shallow-water sedimentary sequence that includes quartz-pebble conglomerate, quartzite, metapelite, and metacarbonates. These rocks are likely the remnants of a thin passive margin sequence.



Tectonic zonation map of the Archean Slave Province showing ancient Gneissic terrane in the west (Anton terrane) and younger accreted arc in the east (Contwoyto terrane)

The Sleepy Dragon terrane extends from northeast of Yellowknife to the south shore of the south arm of Point Lake. This terrane includes intermediate to mafic quartzofeldspathic gneiss complexes such as the 2.8–2.7 billion-year-old Sleepy Dragon complex in the south, banded and migmatitic gneisses near Beniah Lake, and 3.15 billion-year-old chloritic granite on Point Lake. Isolated dioritic to gabbroic bodies are found as inclusions and enclaves. The most common protoliths to the gneisses are tonalites and granodiorites, and rock types in the Sleepy Dragon terrane are broadly similar to those in the Anton terrane. Sleepy Dragon gneisses are locally overlain unconformably by shallow water sedimentary sequences, notably along the southeastern margin of the complex near Detour Lake. Here, a basal tonalite, pebble-bearing conglomerate grades up into metaquartzose and calcareous sands, and then into a metacarbonate sequence consisting of marbles and calc-silicate minerals. From base to top this sequence is only 1,600 feet (500 m) thick, but it has been shortened considerably. Several tens of kilometers north at Beniah Lake in the Beaulieu River greenstone belt, up to 3,200 feet (1,000 m) of quartzite are recognized between shear zones. There are thus several locations where shallow water sediments appear to have been deposited on Sleepy Dragon gneisses. The similarities of the lithofacies successions in these rocks to those found in Phanerozoic rift and passive margin sequences are striking.

The Contwoyto terrane is composed of laterally continuous graywacke mudstone turbidites exposed in a series of westward-vergent folds and thrusts. Mapping in the Point Lake area revealed westward-directed thrusts placing high-grade metagraywackes over lower-grade equivalents. The graywackes are composed of matrix, rock fragments (felsic volcanics, mafic volcanics, chert, granite), and feldspars. Typically only the upper parts of the Bouma sequence are preserved. Black shales and iron formations form thin layers, especially near the structural base of the sequence. In many places greenstone belts conformably underlie the sediments, but the bases of the greenstone belts are either known to be truncated by faults or are poorly defined, suggesting that they are allochthonous. Ophiolite-like stratigraphy, including the presence of sheeted dikes and cumulate ultramafics, has been recognized in several greenstone belts. Other greenstone belts of the Contwoyto terrane are composed predominantly of basaltic pillow lavas and exhibit both tholeiitic and calc-alkaline differentiation trends.

Rocks of the Contwoyto terrane thus include tectonic slivers of ophiolite-like rocks, oceanic type sediments (shales, iron formations), and abundant graywackes exhibiting both volcanogenic and flysch-like characteristics. These rocks are contained in westward-verging folds and are disrupted by westward-directed thrusts. A series of granitoids intruded this package of rocks at various stages of deformation. These relationships are characteristic of an accretionary prism tectonic setting. In such an environment graywackes are eroded from a predominantly island arc source, as well as from any nearby continents, and are deposited over ophiolitic basement capped by abyssal muds and iron formations. Advance of the accretionary prism scrapes material off the oceanic basement and incorporates it in westward-vergent fold-and-thrust packages. This material is accreted to the front of the arc, and is intruded by arc-derived magmas during deformation. Metamorphism is of the low-pressure, high-temperature variety and is similar to that of accretionary prisms that have experienced subduction of young oceanic crust or subduction of a ridge segment.

The Hackett River arc consists of a series of northwest striking volcanic piles and synvolcanic granitoids, especially in the south. Felsic volcanics predominate but a spectrum of compositions including basalt, andesite, dacite, and rhyolite is present. Volcanic piles in the Hackett River arc therefore differ strongly from greenstone belts in the west, which consist predominantly of mafic volcanic and plutonic rocks. In the Back River area, cauldron subsidence features, rhyolitic ring intrusions, tuffs, breccias, flows, and domes, with well-preserved subaerial and subaquatic depositional environments, have been documented. Rhyolites from the Back River complex have been dated at 2.69 billion years old, and the volcanics are broadly contemporaneous with graywacke sedimentation because the flows overlie and interfinger with the sediments. Gneissic rocks in the area are not extensively intruded by mafic dike swarms like the gneisses of the Anton and Sleepy Dragon terranes, and they have yielded ages of 2.68 billion years, slightly younger than surrounding volcanics. Since none of the gneisses in the Hackett River arc have yielded ages significantly older than the volcanics, deformed plutonic rocks in this terrane are accordingly distinguished from gneisses in the western part of the Slave Province. These gneisses are suggested to represent subvolcanic plutons that fed the overlying volcanics. Another suite of tonalitic, dioritic, and granodioritic plutonic rocks with ages 60 to 100 million years younger than the volcanics also intrude the Hackett River arc. This suite of granitoids is equated with the late- to post-tectonic granitoids that cut all rocks of the Slave craton.

A belt of graywacke turbidites in the easternmost part of the Slave Province near Beechy Lake has dominantly eastward-vergent folds and possible thrusts, with some west-vergent structures. The change from regional west vergence to eastward vergence is consistent with a change from a forearc accretionary prism to a back-arc setting in the Beechy Lake domain.

The Hackett River terrane is interpreted as an island arc that formed above an east-dipping subduction zone at 2.7 to 2.67 billion years ago. The mafic to felsic volcanic suite, development of caldera complexes, and overall size of this belt are all similar to recent immature island arc systems. The Contwoyto terrane is structurally and lithologically similar to forearc accretionary complexes; west-vergent folds and thrusts in this terrane are compatible with eastward-dipping subduction, as suggested by the position of the accretionary complex to the west of the arc axis. The change from west to east vergence across the arc-axis into the Beechy Lake domain reflects the forearc and back-arc sides of the system. Mafic volcanic belts within the Contwoyto terrane are interpreted as ophiolitic slivers scraped off the subducting oceanic lithosphere.

The Anton terrane in the western part of the Slave Province contains remnants of an older Archean continent or microcontinent including the world's oldest known continental crust. Quartzofeldspathic gneisses here are as old as 4.03 billion years, with more abundant 3.5–3.1 billion-year-old crust. These gneissic rocks were deformed prior to the main orogenic event at 2.6 billion years ago. The origin of the gneisses in the Anton terrane remains unknown; many have igneous protoliths, but the derivation of the rocks is not yet clear. The Sleepy Dragon terrane might represent a microcontinent accreted to the Anton terrane prior to collision with the Hackett River arc, but more likely it represents an eastern part of the Anton terrane uplifted and transported westward during orogenesis. Studies at the southern end of the Sleepy Dragon terrane have shown that the gneisses occupy the core of a large fold or anticlinorium, consistent with the idea that the Sleepy Dragon terrane represents a basement-cored Alpine style nappe transported westward during the main orogenic event. The distribution of pregreenstone sediments lying unconformably over the gneisses is intriguing. At Point Lake, a few meters of conglomerates, shales, and quartzites lie with possible unconformity over the Anton terrane gneiss, whereas farther east, up to 1,600 feet (500 m) of sediments unconformably overlie Sleepy Dragon terrane gneisses. These include basal conglomerates and overlying sand, shale, and carbonate sequences, and thick quartzites with unknown relationships with surrounding rocks. These scattered bits of preserved older sediments in the Slave Province may represent remnants of an east-facing platform sequence developed on the Anton-Sleepy Dragon microcontinent.

In a simple sense, the tectonic evolution of the Slave craton can be understood in terms of a collision between an older continent with platformal cover in the west with a juvenile arc/accretionary prism in the east. The Anton terrane experienced a sequence of poorly understood tectonomagmatic events between 4.03 and 2.9 billion years ago, then was intruded by a set of mafic dikes probably related to lithospheric extension. After extension, the thermally subsiding Anton terrane was overlain by an eastward thickening shallow-water platform sequence. To the east, the Hackett River volcanic arc and Contwoyto terrane are formed as a paired accretionary prism and island arc above an east-dipping subduction zone. Numerous pieces of oceanic crust are sliced off the subducting lithosphere, and synvolcanic plutons intrude along the arc axis. Any significant rollback of the slab or progradation of the accretionary wedge will cause arc magmas to intrude the accreted sediments and volcanics. Graywacke sediments are also deposited on the back side of the system in the Beechy Lake domain.

As the arc and continent collided at about 2.65 billion years ago, large ophiolitic sheets were obducted, and a younger set of graywacke turbidites was deposited as conformable flysch. This is in contrast to other graywackes that were incorporated into the accretionary prism at an earlier stage and then thrust upon the Anton terrane. There are thus at least two ages of graywacke sedimentation in the Slave Province. Older graywackes were deposited contemporaneously with felsic volcanism in the Hackett River arc, whereas younger graywackes were deposited during obduction of the accretionary prism onto the Anton continent. Synvolcanic plutons along the arc axis became foliated as a result of the arc-continent collision, and back-thrusting shortened the Beechy Lake domain. Continued convergence caused the uplift and transportation of the Sleepy Dragon terrane as a basement nappe and strongly attenuated greenstone slivers. Numerous late- to post-tectonic granitoids represent postcollisional anatectic responses to crustal thickening, or pressure-release melts formed during postcollisional orogenic extension and collapse. These suites of granitoids have similar intrusion ages across the province.

Superior Craton

The Superior Province is the largest Archean craton preserved on the planet, with an area of 625,000 square miles (1.6 million km^2). Most rocks within the Superior Province resemble those found at younger subduction zones and in island and continental margin arc sequences, suggesting that the processes involved in forming the Superior Province were the result of plate tectonics. Contrary to popular geological myth that Archean cratons do not show linear tectonic zonations, the Superior Province exhibits strong linear tectonic zones with individual belts extending for thousands of miles (km) in a southwest-northeast arrangement. Some belts are dominated by metasedimentary rocks, others by mafic volcanic and plutonic rocks, high-grade gneisses, or granitoids. Most of these belts are separated from other belts by major fault zones, many of which have long tectonic histories. In general these different belts are older and were joined with each other at older ages in the north, extending back to 3.0 billion years ago, and get progressively younger to the south until the ages are about 2.7 billion years along the Canadian/United States border. The final belt to the south, however, is the Minnesota River Valley Province, with ages of old gneisses that extend back to 3.66 billion years. This old terrane probably represents an older continental fragment that the rest of the Superior Province was accreted to around 2.7 billion years ago.

The Minnesota River Valley Province occupies the southwest corner of the Superior Province and includes an assemblage of granitic gneisses and amphibolites with ages that go back to 3.66 billion years ago. These rocks experienced their first deformation event at 3.6 billion years ago, with additional deformation and metamorphic events at 3.05 and 2.7 billion years ago. This older continental block is separated from the Wawa terrane to the north by a major structure called the Great Lakes tectonic zone, interpreted to be a suture along which the terranes to the north were thrust southward over the Minnesota foreland.

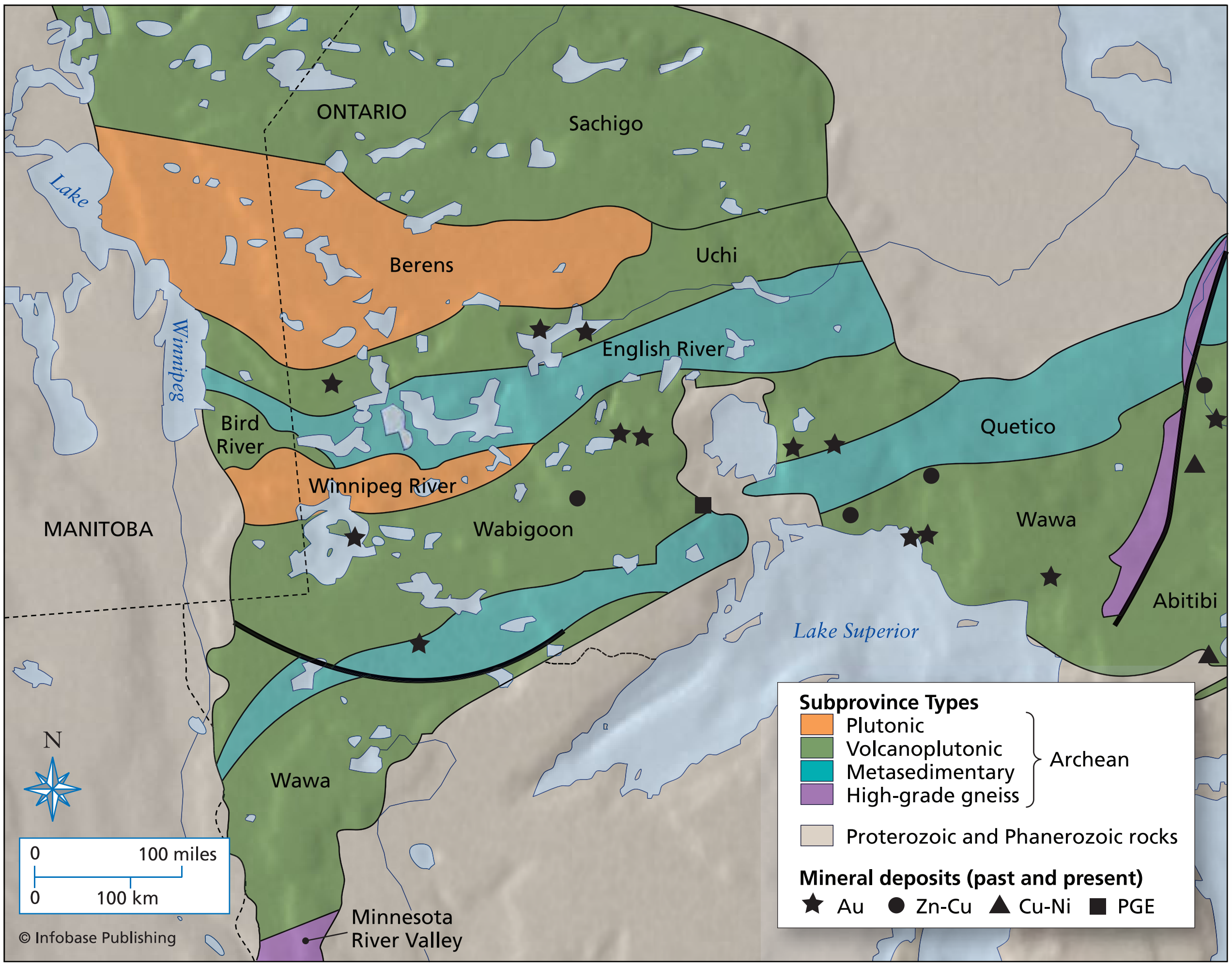
The Wawa terrane consists of a thick assemblage of volcanic and sedimentary rocks, and plutons that largely represent the deeper level equivalent to the volcanic rocks. Most of the volcanic and plutonic rocks are 2.75 to 2.71 billion-year-old tholeiitic basalts intercalated with tholeiitic to calc-alkaline mixed mafic and felsic volcanics. These are intruded by a suite of tonalitic plutons, then a series of post-deformational plutons with ages of 2.68 billion years. The Wawa terrane is therefore interpreted as an island arc that formed at 2.75–2.71 billion years ago and was thrust over the Minnesota foreland by 2.68 billion years ago. In the eastern part of the province in Quebec, rocks of the Wawa terrane are tilted upward on a major crustal-scale shear zone known as the Kapuskasing structure that formed in the Early Proterozoic around 1.9 billion years ago, and uplifts from as deep as 12 miles (20 km) to the surface. The origin of the uplift is thought to be from a distant continent-continent collision such as along the Trans-Hudson orogen, forming an intracontinental uplift similar to the Tien Shan north of the contemporaneous India-Asia collision.

To the east of the Kapuskasing uplift, the Abitibi belt forms a wide area of island arc type rocks similar in aspect and age to the Wawa belt, with 2.73 to 2.70 billion year old basaltic to komatiitic lava complexes intruded by diorite-tonalite-granodiorite plutons and intruded by 2.7 to 2.67 billion-year-old suites of more silicic volcanic rocks. The Abitibi province is the site of many gold mines, with many of them hosted in quartz veins in shear zones. Other massive sulfide deposits are directly associated with the volcanic rock sequences. A group of strongly deformed turbidites called the Pontiac belt on the south side of the Abitibi belt is interpreted to be an accretionary prism associated with the Abitibi arc.

The Quetico Province is a large metasedimentary belt located north of the Wawa arc, consisting of strongly folded and sheared graywacke turbidites, conglomerates, and other rocks derived from a mixed mafic and felsic volcanic source. The belt is metamorphosed more strongly in the center of the belt than along its margins. The most reasonable interpretation of the Quetico is that it is a large accretionary prism terrane composed of trench-fill turbidites that formed the forearc to the Wabigoon arc to the north. Late stage deformation of the Quetico belt reflects dextral oblique subduction beneath the Wawa belt to the south.

The Wabigoon terrane probably formed as a south-facing island arc terrane. This arc is similar in terms of rock types to the other arcs in the south, but the age of deformation (2.71 to 2.70 billion years) is about 10 million years older than farther south in the Wawa and Abitibi belts and about 20 million years younger than in the arcs to the north. These relationships support a general north to south accretion of arc and accretionary prism terranes in the Superior Province during the Archean. The Wabigoon terrane is unusual though, in that it has some older gneissic fragments with ages of about 3.0 billion years old, and these are overlain by locally thick (~1,600 feet; 500 m) limestone and dolostone sequences with shallow-water stromatolites, interpreted to be remnants of a passive margin sequence later overthrust by the arc sequence.

The English River accretionary prism lies north of the Wabigoon arc and is similar in aspect to the Pontiac and Quetico belts. The English River belt is located between the Wabigoon arc and the Uchi-Sachigo arc to the north. Its northern boundary is a major dextral/south over north thrust, and deformation can be shown to have ended by 2.66 billion years ago based on the ages of cross-cutting undeformed granitic rocks. The Uchi-Sachigo island arc shows three distinct periods of magmatism at 2.93, 2.83, and 2.73 billion years ago, and deformation at 2.73 to 2.72 billion years ago, about 20–30 million



Map of the western Superior Province showing division into plutonic, volcano-plutonic, metamorphic, and metasedimentary subprovinces. The volcanic and volcano-plutonic subprovinces are interpreted to represent ancient island arc and continental arc terranes, whereas the metasedimentary subprovinces are interpreted to represent accretionary prisms that formed on the margins of these arcs. The metamorphic terranes include fragments of older continents. Collision of the arcs, accretionary prisms, and continental fragments formed the Superior Province. Large strike-slip faults currently separate many of the individual subprovinces. (Map modified after Ken Card and John Percival.)

years before deformation in the southern Superior Province.

The northwest part of the Superior Province consists of the Pikwitonei uplift and Thompson belt, consisting largely of high-grade granulites that are interpreted to represent a very deeply eroded section of the Sachigo arc terrane. The metamorphism and late deformation is related to the Proterozoic events in the 1.9 to 1.8 billion-year-old Trans-Hudson belt that borders the Superior Province just to the north and west of this location.

The northeastern part of the Superior Province is called the Minto block, and it was largely regarded as one of the world's largest granulite facies terranes until mapping in the late 1990s and 2000s by Geological Survey of Canada geologists led by John Percival divided the block into a number of different terranes of different character. These include the Inukjuak terrane, Tikkerutuk terrane, and Lake Minto domains in the west that consist largely of granitic and granulitic gneisses, the Goudalie and Qalluviartuuq belts in the center of the block, consisting of oceanic assemblage ophiolitic and arc rocks tectonically mixed with metasediments, and in the east another group of granitoid and granulitic rocks in the Utsalik, Lepelle, and Douglas Harbour terranes. In a general way these are interpreted as two arc/continental fragments that collided across a closed ocean basin preserved in the Goudalie and Qalluviartuuq belts.

Wyoming and Churchill Cratons

The Wyoming craton is exposed discontinuously in the Laramide ranges of Wyoming and Montana. Rocks in the province include abundant shelf-type metasedimentary rocks, including quartzite, marble, and pelite, and older crust consisting of 3.6 to 3.1 billion-year-old granulites and gneisses. The rocks have been complexly folded and sheared, making correlations difficult, but most seem to have been deformed and assembled between 2.9 and 2.6 billion years ago. A late Archean suture has been interpreted to cut the southern part of the province in the Wind River Range and has a possible Archean ophiolite associated with the suture.

The Churchill Province consists of a number of different Archean and reworked Archean blocks separated by Proterozoic orogenic belts. Most important among these Archean blocks are the Hearne Province, which extends from the Wyoming craton in the south to Hudson Bay, and the Rae Province, which lies on the northwest side of the Hearne Province across the Snowbird tectonic line and extends to the Canadian Arctic islands. The Hearne Province is separated from the Superior craton by the Proterozoic Trans-Hudson orogen, and the Rae Province is separated from the Slave Province by the Thelon-Talston arc and orogen.

The Hearne Province is a Late Archean province consisting mostly of arc magmatic rocks but containing infolded remnants of platformal cover rocks and foreland basin sequences. The core of the Hearne Province consists of low-grade rocks in its core, with a progressive increase in metamorphic grade and the amount of strain outward toward the province boundaries until granulite grade is reached on its margins. The arc sequence in the core consists of submarine volcanic rocks and volcanogenic sediments, intruded by plutons of gabbro, diorite, tonalite and granite. Felsic volcanic rocks in the core of the Hearne Province have ages of 2.7 to 2.68 billion years.

Rocks in the Rae Province consist predominantly of Late Archean (~2.8 billion-year-old) quartzofeldspathic gneisses, enclosing belts of mafic volcanic and plutonic rocks, quartzites, iron formations, and graywacke-pelite assemblages. Some of the rocks enclosed in the gneiss have ages of 2.9–2.8 billion years, and a few are up to 3.1 billion years.

PROTEROZOIC ASSEMBLY OF THE CORE OF NORTH AMERICA

Most of the core of North America was assembled by the collision of Archean cratons in the Paleoproterozoic, between 2.5 and 1.6 billion years ago. Paleomagnetic data from the Slave, Superior, Churchill, and Wyoming cratons all show relative convergence of thousands of miles (up to 4,000 km) in the Late Paleoproterozoic, and wide collisional orogens developed between these cratons. At this time the Churchill Province consisted of the previously joined Rae and Hearne Provinces, and probably also the Wyoming craton in the south. These were joined with Baltica to form a Late Paleoproterozoic supercontinent called Nuna, after an Inuit name for the lands bordering the northern oceans.

During the formation, Nuna oceanic crust was subducted beneath the Churchill Province, forming extensive belts of Paleoproterozoic plutonic rocks that form large convergent margin arc sequences, now deeply eroded. The margins of the Slave and Superior cratons that collided with the Churchill show more passive margin–type sequences, and as the magmatically thickened and heated crust of the Churchill Province was caught between the colliding Slave and Superior cratons, it became strongly deformed and was extruded laterally in escape tectonics as the convergence continued. The extrusion was accompanied by thickening of the province, which formed a large collisionally thickened plateau, similar to deep levels of the Tibetan plateau forming in the present plate mosaic as a result of the India-Asia collision. The Churchill Province therefore preserves many large continental scale ductile shear zones formed during the Paleoproterozoic amalgamation of Nuna. After the collision was complete, the Churchill Province experienced extensional collapse and then intrusion of post-orogenic granitoid rocks, including rapakivi granites and other intraplate magmas.

The margins of the Slave and Superior cratons that collided with the Churchill Province in the Late Paleoproterozoic show large-scale fold-thrust belts and nappes that were directed away from the core of the orogen in the Churchill Province. The rocks in these fold-thrust belts include rifted margins formed between 2.1 and 2.0 billion years ago overlain by passive margin sediments that were caught in the thrusting at 1.6–1.9 billion years ago.

Some of the Paleoproterozoic suture zones surrounding the Superior craton contain remnants of closed oceans. On the Ungava Peninsula a 2.0 billion-year-old ophiolite, 1.92 billion-year-old oceanic plateau, and 1.87–1.83–billion-year-old oceanic island arc were thrust over a rifted margin of the Superior craton to the south, and similar sequences are known from the western side of Hudson's Bay. Overall, the structural style and types of rocks in these Paleoproterozoic orogens are very similar to orogenic belts formed in the Paleozoic and younger times.

During the formation of the Nuna supercontinent, the Slave, Superior, and other smaller blocks including the Nain craton collided with the Churchill Province, and these cratons all had passive margins on their trailing, or back sides. Soon after they collided with the Churchill Province, most of these passive margins experienced collision of arc terranes; then the direction of subduction along those margins reversed, so that after the collision, the margins were converted to Andean-style convergent margins. On the western side of the Slave Province the Wopmay orogen formed in this way, where a rift to passive margin formed on the Slave crust and was followed by the accretion of an arc and collision with the Great Bear magmatic arc at 1.88 billion years ago. Other belts experienced similar collisions at 1.85 and 1.84 billion years ago, showing that material continued to be accreted to Nuna, or ancestral North America, after the heartland formed.

The growth of North America continued at 1.8 to 1.6 billion years ago with the accretion of juvenile crust that underlies much of the Central Plains and the southwestern United States in the Central Plains, Yavapai, and Mazatzal orogens.

In the Mesoproterozoic from 1.6 to 1.0 billion years ago, the tectonics of North America were dominated by the formation of the Grenville orogen. The Grenville orogen forms a belt of high-grade metamorphic rocks that stretches from Newfoundland and Labrador through eastern Canada to the Great Lakes and Adirondack region of the United States, then through to Texas and the Sierra Madre of Mexico. The Grenville orogen is part of a worldwide belt of similar orogens with a total length of more than 6,000 miles (10,000 km) that formed as many continental nuclei and cratons similar in aspect to North America collided to form the supercontinent of Rodinia. These continental fragments included North America, Baltica, Amazonia, West Africa, the Kalahari craton, Congo craton, India, Australia, and parts of Siberia. Rodinia existed as a supercontinent from about 1.0 billion years ago until about 750 million years ago, when widespread rifting caused many of these fragments to be dispersed in a new phase of breakup in the supercontinent cycle. Some of the continents rifted off somewhat earlier, some even as early as 900 million years ago, not very long after Rodinia had just finished forming.

After the breakup of Rodinia in the Mesoproterozoic, many of the continental fragments reassembled on the opposite side of the globe in an "inside-out" configuration, where fragments formerly on the exterior parts of Rodinia found themselves located on the inside of the next supercontinent, Gondwana. This progressive breakup and reamalgamation also left formerly interior parts of the continents, including North America, outside the Gondwana supercontinent altogether or located on its outer fringes. Gondwana formed by the joining of the main blocks of the Congo and Kalahari cratons, West Africa, Amazon and Rio del Plata cratons, India, East Antarctica, and Australia at about 545 million years ago.

During the evolution of Gondwana, North America formed a northern supercontinent known as Laurentia. During the Paleozoic and Mesozoic, North America saw its most significant evolution along the western and eastern margins of the continent, in the Cordilleran or Rocky Mountain fold belts and the Applachian-Ouachita orogen. Other belts on the fringes of North America include the Caledonian belt and the Innuitian belt in the Canadian Arctic.

APPALACHIANS

The Appalachian Mountain belt extends for 1,600 miles (2,600 km) along the east coast of North America, stretching from the St. Lawrence Valley in Quebec, Canada, to Alabama. Many classifications consider the Appalachians to continue through Newfoundland in maritime Canada, and before the Atlantic Ocean opened, the Appalachians were continuous with the Caledonides of Europe. The Appalachians are one of the best-studied mountain ranges in the world, and understanding of their evolution was one of the factors that led to the development and refinement of the paradigm of plate tectonics in the early 1970s.

Rocks that form the Appalachians include those that were deposited on or adjacent to North America and thrust upon the continent during several orogenic events. For the length of the Appalachians, the older continental crust consists of Grenville Province gneisses, deformed and metamorphosed about 1.0 billion years ago during the Grenville orogeny. The Appalachians grew in several stages. After Late Precambrian rifting, the Iapetus Ocean evolved and hosted island arc growth, while a passive-margin sequence was deposited on the North American rifted margin in Cambrian-Ordovician times. In the Middle Ordovician, the collision of an island arc terrane with North America marks the Taconic orogeny, followed by the mid-Devonian Acadian orogeny, which probably represents the collision of North America with Avalonia, off the coast of Gondwana. This orogeny formed huge molassic fan delta complexes of the Catskill Mountains and was followed by strike-slip faulting. The Late Paleozoic Alleghenian orogeny formed striking folds and faults in the southern Appalachians, but was dominated by strike-slip faulting in the Northern Appalachians. This event appears to be related to the rotation of Africa to close the remaining part of the open ocean in the southern Appalachians. Late Triassic-Jurassic rifting reopened the Appalachians, forming the present Atlantic Ocean.

The history of the Appalachians begins with rifting of the 1-billion-year-old Grenville gneisses and the formation of an ocean basin known as Iapetus approximately 800–570 million years ago. Rifting was accompanied by the formation of normal-fault systems and grabens and by the intrusion of swarms of mafic dikes exposed in places in the Appalachians, such as in the Long Range dike swarm on Newfoundland's Long Range Peninsula. Rifting was also accompanied by the deposition of sediments, first in rift basins and then as a Cambrian transgressive sequence that prograded onto the North American craton. This unit is generally known as the Potsdam sandstone, and is well exposed around the Adirondack dome in northern New York State. Basal parts of the Potsdam sandstone typically consist of a quartz pebble conglomerate and a clean quartzite.

Overlying the basal Cambrian transgressive sandstone is a Cambrian-Ordovician sequence of carbonate rocks deposited on a stable carbonate platform or passive margin, known in the northern Appalachians as the Beekmantown Group. Deposition on the passive margin was abruptly terminated in the Middle Ordovician when the carbonate platform was progressively uplifted above sea level from the east, migrated to the west, and then suddenly dropped down to water depths too great to continue production of carbonates. In this period, black shales of the Trenton and Black River groups were deposited, first in the east and then in the west. During this time, a system of normal faults also migrated across the continental margin, active first in the east and then in the west. The next event in the history of the continental margin is deposition of coarser-grained clastic rocks of the Austin Glen and correlative formations, as a migrating clastic wedge, with older rocks in the east and younger ones in the west. Together, these diachronous events represent the first stages of the Taconic Orogeny, and they represent a response to the emplacement of the Taconic allochthons on the North American continental margin during Middle Ordovician arc-continent collision. In some places, an event that predates the Taconic orogeny, and postdates the late Precambrian is preserved and is known as the Penobscottian orogeny.

Penobscottian Orogeny

The northern Appalachians have been divided into a number of different terranes or tectonostratigraphic zones, reflecting different origins and accretionary histories of different parts of the orogen. The North American craton and overlying sedimentary sequences form the Humber zone, whereas fragments of peri-Gondwanan continents are preserved in the Avalon zone. The Dunnage terrane includes material accreted to the North American and Gondwanan continents during closure of the Paleozoic Iapetus Ocean. Gander terrane rocks were initially deposited adjacent to the Avalonian margin of Gondwana. A piece of northwest Africa left behind during Atlantic rifting is preserved in the Meguma terrane. For many years a pre-Middle Ordovician (Taconic age) deformation event has been recognized from parts of central Maine, New Brunswick, and a few other scattered parts of the Appalachian orogen. This Late Cambrian-Early Ordovician event probably occurred between two exotic terranes in the Iapetus Ocean, before they collided with North America, and is known as the Penobscottian orogeny in the northern Appalachians.

Because the Penobscottian orogenic deformation is less extensive than other orogenies in the Appalachians, interpretations have been based on information from limited areas; thus a comprehensive model is difficult to propose. The deformation is confined to the Gander terrane in the Northern Appalachians and the Piedmont in the Southern Appalachians. The timing of this orogenic event can be best determined in western Maine, where an exposure of sialic basement, an ophiolite, and associated accretionary complexes crop out. It has also been suggested that the Brunswick subduction complex in New Brunswick, Canada, represents the remains of the Penobscottian orogeny. In western Maine, the major units include the Chain Lakes massif, interpreted to be Grenville age; the Boil Mountain ophiolite, interpreted to be a relict of oceanic crust obduced during accretion of the Boundary Mountains terrane to the previously existing Gander terrane; and the Hurricane Mountain mélange, expressing the flysch deposits of the accretionary prism during amalgamation. These rock units together record a portion of the complex deformational history of the closing of the Iapetus Ocean. The Boil Mountain ophiolite occurs in a structurally complex belt of ophiolitic slivers, exotic microterranes (e.g., Chain Lakes massif), and mélange along the boundary between the Dunnage and Gander terranes in central Maine. Its geological evolution is critical to understanding the Late Cambrian-Early Ordovician Penobscottian orogeny.

The Penobscottian orogeny in the Northern Appalachians was initiated sometime during the Late Cambrian. Isotopic ages of the Boil Mountain ophiolite range from 500–477 million years old. Fossil evidence further supports this Middle Cambrian to Early Ordovician age range. Sponges of this age have been found in the black shales of the Hurricane Mountain mélange, constraining the maximum age for the mélange.

The Boil Mountain ophiolite and the associated Chain Lakes massif are instrumental in the interpretation of the Penobscottian orogeny. In order to better comprehend their relationship, it is important to understand their lithologies and regional context.

The Chain Lakes massif is characterized by meta diamictite that is composed of mostly metasandstone, minor amphibolite, granofels, and gneiss. The structure has been interpreted to be an elongate dome with an estimated exposed thickness of 9,840 feet (3,000 m). The unit is bounded by faults that strike northwest and comes in contact with several intrusive bodies, including the Attean batholith to the northeast and the Chain of Ponds pluton to the southwest. Along its eastern and western margin, Silurian and Devonian strata overlie the massif. The Boil Mountain ophiolite is in fault-bounded contact with the Chain Lakes massif on its southern and southeastern margin. Seismic reflection profiling has shown that the Chain Lakes massif is floored by a major fault dipping toward the southeast. This was interpreted to represent a thrust that originated to the southeast and formed during either the Acadian or the Taconic orogenies.

The massif may be divided into eight facies based on structural aspects and lithology of the complex. The structurally lowest sequence is first divided into three facies: (1) the Twin Bridges semipelitic gneiss, (2) the Appleton epidiorite, and (3) the Barrett Brook polycyclic epidiorite breccia. The next four facies represent the principal diamictite sequence and include (1) the McKenney Pond chaotic rheomorphic granofels, (2) the Coburn Gore semipelitic gneissic granofels, (3) the Kibby Mountain flecky gneiss, and (4) the Sarampus Falls massive to layered granofels. The structurally highest facies is the Bag Pond Mountain bimodal metavolcanic section and feldspathic meta-arenite. The highest facies are interpreted to represent the return to a passive margin sequence after metamorphism and deformation. However, the structural and metamorphic history of the area is complicated, and it is difficult to be certain about stratigraphic relationships across structural boundaries.

The metamorphic history of the Chain Lakes massif is one of repeated deformation over a long span of time. The metamorphism of this complex spans a period of 800 million years and has been interpreted to record a pressure-temperature time path of prograde and retrograde events that end with the emplacement of the Late Ordovician batholith. Isotopic ages of the Chain Lakes massif range from approximately 1,500 to 684 million years. The wide variance in the ages may be caused by deposition of material in the massif sometime between these ages as the deformational history was proceeding, or the zircons that produced the Precambrian dates must have been derived from a preexisting Precambrian unit that was eroding into the basin. The diamictite may have been deposited as an alluvial fan type of conglomerate along the rifted margin of the Iapetus and subsequently overridden by the Boil Mountain ophiolite complex.

The Boil Mountain ophiolite lies in fault-bounded contact with the Chain Lakes massif along its southern boundary. This complex extends about 20 miles (30 km) along strike and has a maximum exposure across strike of about four miles (6 km). Units typical of ophiolites such as serpentinite, pyroxenite, metagabbro, and mafic volcanics and sediments consisting of metaquartzwacke, metapelite, slate, and metaconglomerate characterize the Boil Mountain ophiolite. The stratigraphic units consist of, from bottom to top: an ultramafic unit, a gabbroic unit, a tonalitic unit, mafic and felsic volcanics, and metasedimentary units. Thus, the ophiolite has all the components of an ophiolite sequence except the tectonite ultramafic unit and the sheeted dike unit. The basal contact is difficult to differentiate in the large scale, but any contacts that are present suggest that ductile faulting accompanied their emplacement. However, some of the units, including the serpentinite, are in sharp structural contact with the Chain Lakes massif along its southern boundary.

The complex may be divided based on chemistry into several units, including ultramafics, gabbros, two mafic volcanic units, and felsic volcanics. A felsic unit separates the two mafic volcanic units, termed upper and lower. Geochemical patterns reveal two distinct crystallization trends within the complex. The first magma to be erupted was the lower mafic volcanic unit. Geochemical trends suggest that the crystallization of olivine, clinopyroxene, and plagioclase resulted in this magma composition. This is accomplished by the formation of the ultramafics and gabbroic unit. The upper mafic unit has geochemical affinities to an island arc tholeiite (IAT) zone, while the upper mafic unit is similar to mid-ocean ridge basalts (MORB). Since there is such a large volume of felsic material associated with the ophiolite, it is likely that there were two phases of extrusion for the mafic volcanic unit. Because the presence of tonalites and other felsic volcanic rocks implies that there must be hydrous fluids, the first phase must include a subduction zone. The lower mafic unit and the felsics represent this phase. The upper mafic unit suggests that volcanism occurred in a marginal basin, because the mantle source for these units was not affected by the subducting slab.

The presence of tonalites in the Boil Mountain ophiolite, with small amounts of trondhjemite, is an unusual feature not found in normal ophiolite sequences. Other ophiolites that include a unit of tonalite are the Semail ophiolite in Oman and the Canyon Mountain ophiolite in California. Tonalites suggest the presence of fluids during crystallization and are instrumental in the interpretation of the ophiolites. The placement of these ophiolites with respect to the rest of the sequence is also of interest. The tonalite of the Boil Mountain complex appears in the sequence above the gabbros and below the volcanogenic units. It has the form of a sill, with abundant intrusive contacts evident in float and rare, poorly exposed outcrops in the northeast part of ophiolite. The tonalite was probably derived from partial melting of the lower mafic volcanics and gabbros, which then intruded as a sill.

The Boil Mountain ophiolite tonalite has yielded an isotopic age of 477 ± 1 million years. The age of 477 million years places a minimum plutonic age for the tonalites of the Boil Mountain ophiolite, which is significantly less than any previously determined age associated with the ophiolite. A Late Cambrian to Early Ordovician age for the Boil Mountain ophiolite has been previously suggested, based on several pieces of information. Felsic volcanics in the upper part of the ophiolite give an age of 500 Ma ± 10 million years. The age of 477 million years for the Boil Mountain tonalites is interpreted as a late-stage intrusive event, possibly related to partial melting of hydrated oceanic crust and the intrusion of a tonalitic extract.

A comparison of the age of the Boil Mountain ophiolite with nearby ophiolitic sequences in the Taconic allochthons of Quebec shows that ophiolite obduction was occurring on the Humber zone of the Appalachian margin of Laurentia, at similar times to the Boil Mountain ophiolite being emplaced over the Chain Lakes massif, interpreted as a piece of the Gander margin of Gondwana. Hornblendes from the metamorphic aureole to the Thetford Mines ophiolite have yielded isotopic ages of 477 ± 5 million years, with an initial detachment age of 479 ± 3 million years for the ophiolitic crust. Detachment of the circa 479 million-year-old sheet began at a ridge segment in a fore arc environment, in contrast to an older, circa 491 ± 11 million-year-old oceanic slab preserved as the Pennington sheet in the Flintkote mine that is interpreted as a piece of oceanic crust originally attached to Laurentia. Thus, there may be a protracted history of Taconian ophiolite obduction in the Quebec Appalachians. In Gaspé, a basal amphibolite tectonite gave an emplacement age of 456 ± 3 million years for the Mount Albert ophiolite.

The age and origin of the tonalites of the Boil Mountain ophiolite and their relationships to the Chain Lakes massif have considerable bearing on the Penobscottian orogeny. First, since tonalitic intrusives are confined to the allochthonous Boil Mountain ophiolite, it can be inferred that the ophiolite was not structurally emplaced in its final position over the Chain Lakes massif until after 477 million years ago (Arenigian). This does not however preclude earlier emplacement (previous to tonalite intrusion) of the ophiolite in a different structural position. Dates for the Taconic orogeny range from 491 to 456 million years ago. Early ideas for the Penobscottian orogeny suggested that it took place prior to the Taconic orogeny. However, it seems more likely that these two orogenies were taking place at the same time, although not necessarily on the same margin of Iapetus.

Geochemical data suggests a two-stage evolution for the Boil Mountain ophiolite, including an early phase of arc or forearc volcanism, followed by a tholeiitic phase of spreading in an intra-arc or back-arc basin. The first phase includes felsic volcanics dated at 500 ± 10 million years, and the second phase, associated with partial melting of the older oceanic crust and the formation of the upper volcanic sequence, occurred at 477 ± 1 million years ago. This tectonic setting is compatible with the IAT characteristics of the lower volcanic unit, and the MORB characteristics of the upper mafic volcanic unit of the ophiolite. Sedimentary rocks intercalated with the upper volcanic unit include iron formation, graywacke, phyllite, and chert, consistent with deposition in a back-arc basin setting. The tonalites formed by hydrous melting of mafic crust of the lower volcanic unit during the initial stages of back-arc basin evolution.

The Boil Mountain ophiolite and Chain Lakes massif thus reveal critical insights about the Penobscottian orogeny. The lower volcanic group of the Boil Mountain ophiolite are island arc tholeiites formed within an immature arc setting 500 million years ago. This phase of volcanism is similar to other Exploits subzone (Dunnage zone) ophiolites, such as the 493 million-year-old Pipestone Pond complex, the 489 million-year-old Coy Pond complex, the South Lake ophiolite of Newfoundland, and 493 million-year-old rhyolites associated with serpentinites of the Annidale area of southern New Brunswick. The Pipestone Pond and Coy Pond complexes both occur as allochthons overlying domal metamorphic cores of Gander zone rocks (Mount Cormack and Meelpaeg Inliers) in a structural arrangement reminiscent of the Boil Mountain complex resting on the margin of the Chain Lakes massif. These ophiolites, including the Boil Mountain ophiolite, probably represent part of the Penobscot arc, which developed in the forearc over a west-dipping subduction zone near the Gander margin of Gondwana.

The 513 million-year-old Tally Pond volcanics of the Lake Ambrose volcanic belt of south-central Newfoundland may also be time-correlative with the lower volcanics of the Boil Mountain ophiolite; both preserve a mixed mafic-felsic volcanic section with arc-related geochemical affinities, and both are interpreted as parts of the Penobscot-Exploits arc accreted to Gondwana in the Early Ordovician. Thus, the Boil Mountain, Coy Pond, and Pipestone Pond ophiolites formed the forearc to the Penobscot-Exploits arc, and the Lake Ambrose volcanic belt represents volcanism in more central parts of the arc. Obduction of Exploits subzone forearc ophiolites over Gander zone rocks in Newfoundland and New Brunswick occurred in Tremadocian-Arenigian times (490–475 million years ago). This was followed by arc reversal in the Arenigian (475–465 million years ago), which formed a new arc (Popelogan arc in northern New Brunswick) and a back-arc basin (Fournier group ophiolites at 464 Ma) that widened rapidly to accommodate the collision of the Popelogan arc with the Notre Dame (Taconic) arc by 445 million years ago. This rifting event may have detached a fragment of Avalonian basement and Gander zone sediments, with overlying allochthonous ophiolitic slabs, now preserved as the Chain Lakes massif and the lower sections of the Boil Mountain ophiolite.

A second episode of magma generation in the Boil Mountain ophiolite is represented by the upper tholeiitic volcanic unit and by the 477 million-year-old tonalite sill, generated by partial melting of the lower volcanic unit. This phase of magma generation is associated with development of the Tetagouche back-arc basin behind the Popelogan arc during Late Arenigian-Llanvirnian. The timing of this event appears to be similar in southern Newfoundland, where several Ordovician granites, including the 477.6 ± 1.8 million-year-old Baggs Hill granite, and the 474 ± 3 million-year-old Partridgeberry Hills granite, intrude ophiolites obduced onto the Gondwanan margin during the early Ordovician.

Since the Boil Mountain tonalites are allochthonous and are not known to occur in the rocks beneath the ophiolite, final obduction of the Boil Mountain complex probably occurred after collision of the Popelogan and Notre Dame (Taconic) arcs, during the post-450 million-year-old collision of Gander margin of Avalon with the active margin of Laurentia. This event could be represented by the 445 million-year-old Attean pluton.

As an alternative model to that presented above, the entire Boil Mountain ophiolite complex may have formed in the forearc of the Popelogan arc, which formed after the Penobscot arc collided with the Avalonian margin of Gondwana. In this model, the Boil Mountain ophiolite would be correlative with other 480–475 million-year-old ophiolites of the Robert's Arm-Annieopsquotch belt that occur along the main Iapetus suture between the Notre Dame (Taconic) arc accreted to Laurentia, and the Penobscot-Exploits arcs accreted to Gondwana. This model would help explain why no evidence of pre-477 million-year-old obduction-related fabrics has been documented from the Boil Mountain complex-Chain Lakes massif contact, but it does not adequately account for the Cambrian ages of the lower volcanic unit of the Boil Mountain ophiolite.

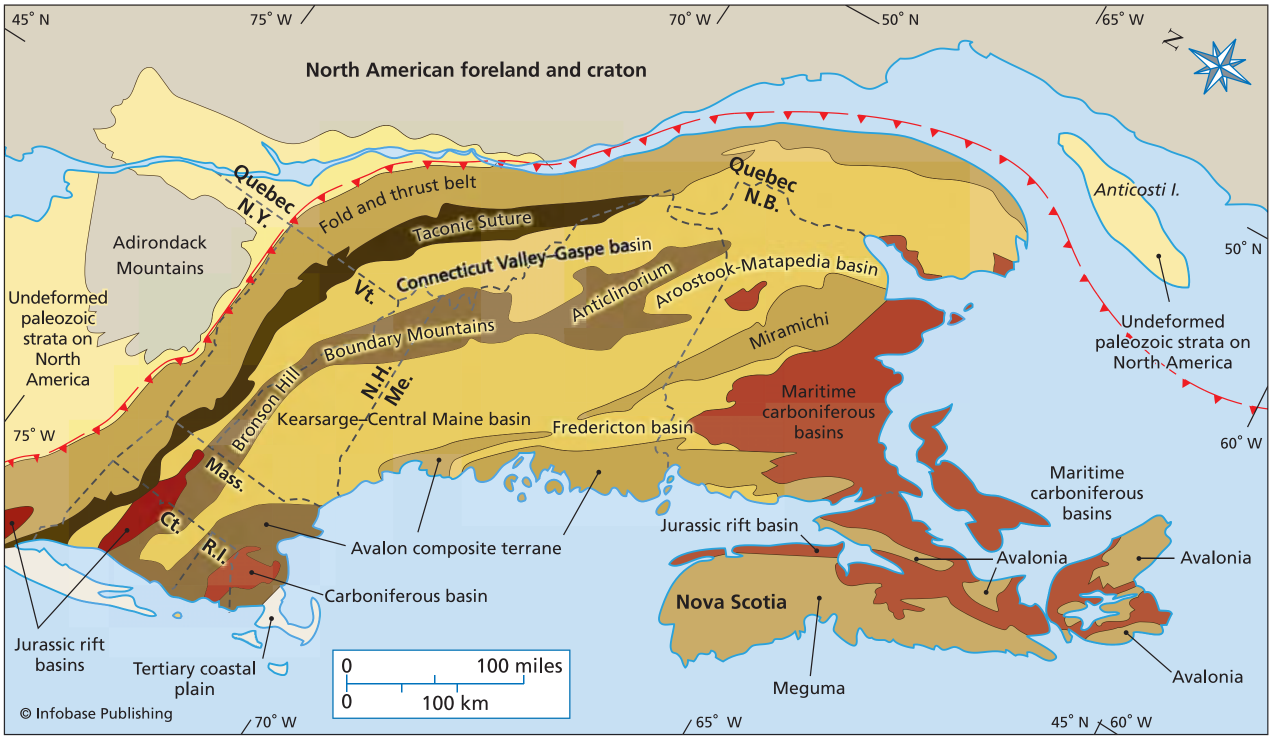
The Penobscottian orogeny has presented difficulties to geologists for quite some time. However, recent studies of the exposure in Maine, including the Chain Lakes unit and the Boil Mountain ophiolite, have led to new models for the tectonic evolution of this complex terrane. New isotopic dates and geochemical evidence show that the Taconian and Penobscottian orogenies were most likely simultaneous events. The models presented in this entry take into account several factors, including the formation of the Chain Lakes unit, the timing of emplacement of the ophiolite, and the timing of the intrusion of tonalites that are thought to represent the suture of the Gander to the Boundary Mountains terrane.

Taconic Orogeny

The Taconic allochthons are a group of Cambrian through Middle Ordovician slates resting allochthonously on the Cambro-Ordovician carbonate platform. These allochthons are very different from the underlying rocks, implying that there have been substantial displacements on the thrust faults beneath the allochthons, probably on the order of 100 miles (160 km). The allochthons structurally overlie wild flysch breccias that are basically submarine slide breccias and mudflows derived from the allochthons.

Eastern sections of the Taconic-aged rocks in the Appalachians are more strongly deformed than those in the west. East of the Taconic foreland fold-thrust belts, a chain of uplifted basement with Grenville ages (about one billion years) extends discontinuously from Newfoundland to the Blue Ridge Mountains, and includes the Green Mountains of Vermont. These rocks generally mark the edge of the hinterland of the orogen and the transition into greenschist and higher metamorphic facies. Some of these uplifted basement gneisses are very strongly deformed and metamorphosed, and they contain domal structures known as gneiss domes, with gneisses at the core and strongly deformed and metamorphosed Cambro-Ordovician marbles around their rims. These rocks were deformed at great depths.

Also close to the western edge of the orogen is a discontinuous belt of mafic and ultramafic rocks comprising an ophiolite suite, interpreted to be remnants of the ocean floor of the Iapetus Ocean that closed during the Taconic orogeny. Spectacular examples of these ophiolites occur in Newfoundland, including the Bay of Islands ophiolite complex along Newfoundland's western shores.



Tectonic zone map of northern Appalachians showing the Early Paleozoic tectonic terranes

Further east in the Taconic orogen are rocks of the Bronson Hill anticlinorium or terrane that are strongly deformed and metamorphosed and have been affected by both the Taconic and Acadian orogenies. These rocks have proven very difficult to map and have been of controversial significance for more than a century. Perhaps the best interpretation is that they represent rocks of the Taconic island arc that collided with North America to produce the Taconic orogeny.

The Piscataquis volcanic arc is a belt of Devonian volcanic rocks that extends from central Massachusetts to the Gaspé Peninsula. These rocks are roughly coextensive with the Ordovician arc of the Bronson Hill anticlinorium and include basalts, andesites, dacites, and rhyolites. Both subaerial volcanics and subaquatic pillow lavas are found in the belt. The Greenville plutonic belt of Maine (including Mount Kathadin) is included in the Piscataquis arc and is interpreted by some workers to be post-Acadian, but is more typical of syntectonic arc plutons. The Acadian orogeny also deformed the eastern part of the Taconic orogenic belt, which contains some younger rocks deposited on top of the eroded Taconic island arc.

The Taconic allochthons turn out to be continental rise sediments that were scraped off the North American continental margin and transported on thrusts for 60–120 miles (100–200 km) during the Taconic arc continent collision. A clastic wedge (Austin Glen and Normanskill formations) was deposited during emplacement of the allochthons by their erosion and spread out laterally in the foreland. As Taconic deformation proceeded, the clastic wedge, underlying carbonates, and the Grenville basement became involved in the deformation, rotating them, forming the Taconic angular unconformity.

Acadian Orogeny

The Acadian orogeny has historically been one of the most poorly understood aspects of the regional geology of the Appalachians. Some of the major problems in interpreting the Acadian orogeny include understanding the nature of pre-Acadian, post-Taconic basins such as the Kearsarge-Central Maine basin, Aroostook-Matapedia trough, and the Connecticut Valley–Gaspé trough. The existence and vergence of Acadian subduction zones is debated, and the relative amount of post-Acadian strike-slip movements is not well constrained.

Examining the regional geology of the northern Appalachians using only the rocks that are younger than the post-Taconic unconformity yields a picture of several distinctive tectonic belts including different rock types and structures. The North American craton includes Grenville gneisses and Paleozoic carbonates. The foreland basin includes a thick wedge of Devonian synorogenic clastic rocks, such as the

Catskill Mountains, that thicken toward the mountain belt. The Green Mountain anticlinorium is a basement thrust slice, and the Connecticut Valley–Gaspé trough is a post-Taconic basin with rapid Silurian subsidence and deposition. The Bronson Hill-Boundary Mountain anticlinorium (Piscataquis volcanic arc) is a Silurian–mid-Devonian volcanic belt formed along the North American continental margin. The Aroostook-Matapedia trough is a Silurian extensional basin, and the Miramichi massif represents remnants of a high-standing Ordovician (Taconic) arc. The Kearsarge-Central Maine basin (Merrimack trough) preserves Silurian deep-water sedimentary rocks, preserved in accretionary prisms, and is the most likely site where the Acadian Ocean closed. The Fredericton trough is a continuation of the Merrimack trough, and the Avalon Composite terrane (coastal volcanic arc) contains Silurian–Early Devonian shallow marine volcanics built upon Precambrian basement of Avalonia.

Synthesizing the geology of these complex belts, the tectonics of the Acadian orogeny in the Appalachian Mountains can be summarized as follows. The Grenville gneisses and some of the accreted Taconic orogen were overlain by a Paleozoic platform sequence, and by mid-Devonian times the region was buried beneath thick clastics of the Acadian foreland basin, best preserved in the Catskill Mountains. Nearly two miles (3 km) of fluvial sediments were deposited in 20 million years, derived from mountains to the east. Molasse and red beds of the Catskills once covered the Adirondack Mountains, as evidenced by pieces preserved in a diatreme in Montreal. These features are exposed along strike as the Old Red Sandstone in Scotland and on Spitzbergen Island.

The Connecticut Valley–Gaspé trough is a complex basin developed over the Taconic suture that was active from Silurian through Early Devonian. It is an extensional basin containing shallow marine sedimentary rocks and may have formed from oblique strike-slip after the Taconic collision, with subsidence in pull-apart basins. The Aroostook-Matapedia trough is an Ordovician-Silurian turbidite belt, probably a post-Taconic extensional basin, and perhaps a narrow oceanic basin.

The Miramichi massif contains Ordovician arc rocks intruded by Acadian plutons, and is part of the Taconic arc that persisted as a high area through Silurian times and became part of the Piscataquis volcanic arc in Silurian-Devonian times. The coastal volcanic arc (Avalon) is exposed in eastern Massachusetts though southern New Brunswick and includes about 5 miles (8 km) of basalt, andesites, rhyolite, and deep and shallow marine sediments. It is a volcanic arc that was built on Precambrian basement that originated in the Avalonian or Gondwana side of the Iapetus Ocean.

The Kearsarge-Central Maine basin (Fredericton trough) is the location of a major post-Taconic, pre-Acadian ocean that closed to produce the Acadian orogeny. It contains polydeformed deepwater turbidites and black shales, mostly Silurian. The regional structural plunge results in low grades of metamorphism in Maine and high grades in New Hampshire, Massachusetts, and Connecticut. There are a few dismembered ophiolites present in the belt, structurally incorporated in about 3 miles (5 km) of turbidites.

Volcanic belts on either side of the Merrimack trough are interpreted to be arcs built over contemporaneous subduction zones. In the Late Silurian, the Acadian Ocean basin was subducting on both sides, forming accretionary wedges of opposite vergence, and forming the Coastal and Piscataquis volcanic arcs. The Connecticut Valley–Gaspé trough is a zone of active strike-slip faulting and pull-apart basin formation behind the Piscataquis arc. In the Devonian, the accretionary prism complexes collide, and west-directed overthrusting produces a migrating flexural basin of turbidite deposition, including the widespread Seboomook and Littleton formations. The collision continued until the Late Devonian, then more plutons intruded, and dextral strike-slip faulting continued.

Acadian plutons intrude all over the different tectonic zones and are poorly understood. Some are related to arc magmatism, some to crustal thickening during collision. Late transpression in the Carboniferous includes abundant dextral strike-slip faults, disrupted zones, and formed pull-apart basins with local accumulations of several miles of sediments. About 200 miles (300 km) of dextral strike-slip offsets are estimated to have occurred across the orogen.

The Late Paleozoic Alleghenian orogeny in the Carboniferous and Permian included strong folding and thrusting in the southern Appalachians, and formed a fold/thrust belt with a ramp/flat geometry. In the southern Appalachians the foreland was shortened by about 50 percent during this event, with an estimated 120 miles (200 km) of shortening. The rocks highest in the thrust belt have been transported the farthest and are the most allochthonous. At the same time, motions in the northern Appalachians were dominantly dextral strike-slip in nature.

In the Late Triassic-Jurassic, rifting and normal faulting were associated with the formation of many small basins and the intrusion of mafic dike swarms related to the opening of the present day Atlantic Ocean.

ROCKY MOUNTAINS

Extending 3,000 miles (4,800 km) from central New Mexico to northwest Alaska in the easternmost

Cordillera, the Rocky Mountains are one of the largest mountain belts in North America. The mountains are situated between the Great Plains on the east and a series of plateaus and broad basins on the west. Mount Elbert in Colorado is the highest mountain in the range, reaching 14,431 feet (4,399 m). The continental divide is located along the rim of the Rockies, separating waters that flow to the Pacific and to the Atlantic Oceans. The Rocky Mountains are divided into the Southern, Central, and Northern Rockies in the conterminous United States, Canadian Rockies in Canada, and the Brooks Range in Alaska. Several national parks are located in the system, including Rocky Mountain, Yellowstone, Grand Teton, and Glacier National Parks in the United States, and Banff, Glacier, Yoho, Kootenay, and Mount Revelstoke in Canada. The mountains were a major obstacle to traveling west during the expansion of the United States, but western regions opened up when the Oregon trail crossed the ranges through South Pass in Wyoming.

In New Mexico, Colorado, and southern Wyoming the Southern Rockies consist of two north-south ranges of folded mountains that have been eroded to expose Precambrian cores with overlying sequences of layered sedimentary rocks. Three basins are located between these ranges, known as the North, South, and Middle Parks. The southern Rockies are the highest section of the whole range, including many peaks more than 14,000 feet (4,250 m) high.

The Central Rockies in northeastern Utah and western Wyoming are lower and more discontinuous than the southern Rockies. Most are eroded down to their Precambrian cores, surrounded by Paleozoic-Mesozoic sedimentary rocks. Garnet Peak in the Wind River Range (13,785 feet; 4,202 m) and Grand Teton in the Teton Range (13,766 feet; 4,196 m) are the highest peaks in the Central Rockies.

The Northern Rockies in northeastern Washington, Idaho, and western Wyoming extend from Yellowstone National Park to the Canadian border. This section is dominated by north-south trending ranges separated by narrow valleys, including the Rocky Mountain trench, an especially deep and long valley that extends north from Flathead Lake. The highest peaks in the Northern Rockies include Borah Peak (12,655 feet; 3,857 m) and Leatherman Peak (12,230 feet; 3,728 m) in the Lost River Range.

The Canadian Rockies stretch along the British Columbia–Alberta border and reach their highest point in Canada on Mount Robson (12,972 feet; 3,954 m). The Rocky Mountain trench continues 800 miles (1,290 km) north-northwest from Montana, becomes more pronounced in Canada, and is joined by the Purcell trench in Alberta. In the Northwest Territories (Nunavet), the Rockies expand northeastward in the Mackenzie and Franklin mountains and near the Beaufort Sea pick up as the Richardson Mountains that gain elevation westward into the Brooks Range of Alaska. Mount Chamberlin (9,020 feet; 2,749 m) is the highest peak in the Brooks Range.

The Rocky Mountains are rich in mineral deposits including gold, silver, lead, zinc, copper, and molybdenum. Principal mining areas include the Butte-Anaconda district of Montana, Leadville and Cripple Creek in Colorado, Coeur d'Alene in Idaho, and the Kootenay Trail region of British Colombia. Lumbering is an active industry in the mountains, but it is threatened by growing environmental concerns and tourism in the national park systems.

Mesozoic–Early Cenozoic contractional events produced the Rockies during uplift associated with the Cordilleran orogeny. Evidence for older events and uplifts are commonly referred to as belonging to the ancestral Rocky Mountain system. The Rocky Mountains are part of the larger Cordilleran orogenic belt that stretches from South America through Canada to Alaska, and it is best to understand the evolution of the Rockies through a wider discussion of events in this mountain belt. The Cordillera is presently active and has been active for the past 350 million years, making it one of the longest-lived orogenic belts on Earth. In the Cordillera, many of the structures are not controlled by continent/continent collisions as they are in many other mountain belts, since the Pacific Ocean is still open. In this orogen structures are controlled by the subduction/accretion process, collision of arcs, islands, and oceanic plateaus, and strike-slip motions parallel to the mountain belt. Present-day motions and deformation are controlled by complex plate boundaries between the North American, Pacific, Gorda, Cocos, and some completely subducted plates such as the Farallon. In this active tectonic setting the style, orientation, and intensity of deformation and magmatism depend largely on the relative convergence–strike-slip vectors of motion between different plates.

The geologic history of the North American Cordillera begins with rifting of the present western margin of North America at 750–800 million years ago, which is roughly the same age as rifting along the east coast in the Appalachian orogen. These rifting events reflect the breakup of the supercontinent of Rodinia at the end of the Proterozoic, and they left North America floating freely from the majority of the continental landmass on Earth. Rifting and the subsequent thermal subsidence of the rifted margin led to the deposition of Precambrian clastic rocks of the Windemere supergroup and carbonates of the Belt and Purcell supergroups, in belts stretching from southern California and Mexico to Canada. These are overlain by Cambrian-Devonian carbonates, Carboniferous clastic wedges, Carboniferous-Permian carbonates, and finally Mesozoic clastic rocks.

The Antler orogeny is a Late Devonian–Early Carboniferous (350–400 million-year-old) tectonic event formed during an arc-continent collision, in which deep-water clastic rocks of the Roberts Mountain allochthon in Nevada were thrust from west to east over the North American carbonate bank, forming a foreland basin that migrated onto the craton. This orogenic event, similar to the Taconic orogeny in the Appalachian Mountains, marks the end of passive margin sedimentation in the Cordillera, and the beginning of Cordilleran tectonism.

In the Late Carboniferous (about 300 million years ago), the zone of active deformation shifted to the east with a zone of strike-slip faulting, thrusts, and normal faults near Denver. Belts of deformation formed what is known as the ancestral Rocky Mountains, including the Front Ranges in Colorado, and the Uncompahgre uplift of western Colorado, Utah, and New Mexico. These uplifts are only parts of a larger system of strike-slip faults and related structures that cut through the entire North American craton in the Late Carboniferous, probably in response to compressional deformation that was simultaneously going on along three margins of the continent.

The Late Permian–Early Triassic Sonoma orogeny (260–240 million years ago) refers to events that led to the thrusting of deep-water Paleozoic rocks of the Golconda allochthon eastward over autochthonous shallow-water sediments just outboard (oceanward) of the Roberts Mountain allochthon. The Golconda allochthon in western Nevada includes deep-water oceanic pelagic rocks, an island-arc sequence, and a carbonate-shelf sequence and is interpreted to represent an arc/continent collision.

In the Late Jurassic (about 150 million years ago) a new, northwest-striking continental margin was established by cross cutting the old northeast-striking continental margin. This event, known as the early Mesozoic truncation event, reflects the start of continental margin volcanic and plutonic activity that continues to the present day. There is considerable uncertainty about what happened to the former extension of the old continental margin—it may have rifted and drifted away, or may have moved along the margin along large strike-slip faults.

Pacific margin magmatism has been active intermittently from the Late Triassic (220 million years ago) through the Late Cenozoic and in places continues to the present. This magmatism and deformation is a direct result of active subduction and arc magmatism. Since the Late Jurassic, there have been three main periods of especially prolific magmatism, including the Late Jurassic/Early Cretaceous Nevadan orogeny (150–130 million years ago), the Late Cretaceous Sevier orogeny (80–70 million years ago), and the Late Cretaceous/Early Cenozoic Laramide orogeny (66–50 million years ago).

Cretaceous events in the Cordillera resulted in the formation of a number of tectonic belts that are still relatively easy to discern. The Sierra Nevada ranges of California and Nevada represent the arc batholith, and contain high-temperature, low-pressure metamorphic rocks characteristic of arcs. The Sierra Nevada is separated from the Coast Ranges by flat-lying generally unmetamorphosed sedimentary rocks of the Great Valley, deposited over ophiolitic basement in a forearc basin. The Coast Ranges include high-pressure, low-temperature metamorphic rocks, including blueschists in the Franciscan complex. Together, the high-pressure, low-temperature metamorphism in the Franciscan complex with the high-temperature, low-pressure metamorphism in the Sierra Nevada, represent a paired metamorphic belt, diagnostic of a subduction zone setting.

Several Cretaceous foreland fold-thrust belts are preserved east of the magmatic belt in the Cordillera, stretching from Alaska to Central America. These belts include the Sevier fold-thrust belt in the United States, the Canadian Rockies fold-thrust belt, and the Mexican fold-thrust belt. They are all characterized by imbricate-style thrust faulting, with fault-related folds dominating the topographic expression of deformation.

The Late Cretaceous–Early Tertiary Laramide Orogeny (about 70–60 million years ago) is surprisingly poorly understood but generally interpreted as a period of plate reorganization that produced a series of basement uplifts from Montana to Mexico. Some models suggest that the Laramide Orogeny resulted from the subduction of a slab of oceanic lithosphere at an unusually shallow angle, perhaps related to its young age and thermal buoyancy.

The Late Mesozoic-Cenozoic tectonics of the Cordillera saw prolific strike-slip faulting, with relative northward displacements of terranes along the western margin of North America. The San Andreas fault system is one of the major transform faults formed in this interval, formed as a consequence of the subduction of the Farallon plate. Previous convergence between the Farallon and North American plates stopped when the Farallon plate was subducted, and new relative strike-slip motions between the Pacific and North American plates resulted in the formation of the San Andreas system. Remnants of the Farallon plate are still preserved as the Gorda and Cocos plates.

Approximately 15 million years ago the Basin and Range Province and the Colorado Plateau began uplifting and extending through the formation of rifts and normal faults. Much of the Colorado Plateau stands at more than a mile (1.5–2.0 km) above sea level but has a normal crustal thickness. The cause of the uplift is controversial but may be related to heating from below. The extension is related to the height of the mountains being too great for the strength of the rocks at depth to support, so gravitational forces are able to cause high parts of the crust to extend through the formation of normal faults and rift basins.

See also ACCRETIONARY WEDGE; ARCHEAN; CAMBRIAN; CONVERGENT PLATE MARGIN PROCESSES; CRATON; DEFORMATION OF ROCKS; DIVERGENT PLATE MARGIN PROCESSES; ECONOMIC GEOLOGY; FLYSCH; GONDWANA, GONDWANALAND; GRANITE, GRANITE BATHOLITH; OROGENY; PALEOZOIC; PANGAEA; PASSIVE MARGIN; PHANEROZOIC; PRECAMBRIAN; SILURIAN; STRUCTURAL GEOLOGY; SUPERCONTINENT CYCLES.

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nova A nova is a general name for a type of star that vastly increases in brightness (by up to 10,000 times) over very short periods of time, typically days or weeks. The word *nova* comes from the Latin for "new" and stems from early astronomers who thought that nova were new stars appearing in the sky, since the parent stars were too faint to be observed from the Earth before powerful telescopes were invented.

A nova forms when a white dwarf star has a companion, such as in a binary star system, and the companion contributes matter to the white dwarf after its initial death. In a simple system where a white dwarf exists alone, it will cool off indefinitely, approach absolute zero, and be invisible in space. However, in some binary star systems the large gravitational field of the white dwarf can pull material, predominantly hydrogen and helium, away from the companion main sequence star and accrete this material onto the white dwarf. As this gas builds up on the white dwarf surface it heats up and becomes denser until its temperature exceeds 100,000,000 K, at which point the hydrogen ignites and rapidly fuses into helium. This causes a sudden and dramatic flare-up of the surface of the white dwarf over a period of a few days, rapidly burning some of the fuel and expelling the rest of it to space in a nova event. After a few months the star's luminosity and surface temperature return to normal.

In white dwarf–binary star systems in which the companion star is a main sequence star, the material that is transferred off the main sequence star is affected by the rotation of the binary system and the gravitational field between the stars, and this material is forced to swirl around and orbits the white dwarf before it accretes to the surface. This forms what is known as an accretion disk. As the material in the accretion disk orbits the white dwarf, it is heated by friction and begins to glow and emit radiation in the visible, ultraviolet, and X-ray wavelengths and may become brighter than the star itself.

White dwarf–binary systems have the possibility of repeating the cycle of becoming novas many times, and some stars have done this hundreds of times. Such recurrent nova have been known since ancient times, and include systems such as RS Ophiuchi, located about 5,000 light years away in the constellation Ophiuchus; T Coronae Borealis, nicknamed the blaze star, in the constellation Coronos Borealis; and T Pyxidis, located about 6,000 light years from Earth in the constellation Pyxis.

See also ASTRONOMY; ASTROPHYSICS; BINARY STAR SYSTEMS; CONSTELLATION; DWARFS (STARS); STELLAR EVOLUTION; SUPERNOVA.

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ocean basin The surface of the Earth is divided into two fundamentally different types of crust, including relatively light quartz and plagioclase-rich sial, forming the continental regions, and relatively dense olivine and pyroxene-rich sima underlying the ocean basins. The ocean basins are submarine topographic depressions underlain by oceanic (simatic) crust. Ocean basins are quite diverse in size, shape, depth, characteristics of the underlying seafloor topography, and types of sediments deposited on the oceanic crust. The largest ocean basins include the Pacific, Atlantic, Indian, and Arctic Oceans and the Mediterranean Sea, whereas dozens of smaller ocean basins are located around the globe.

The ocean basins' depths were first extensively explored by scientists aboard the H.M.S. *Challenger* in the 1800s, using depth reading from a weight attached to a several-mile (kilometer) long cable that was dropped to the ocean floor. Results from these studies suggested that the oceans were generally about three to four miles (five to six km) in depth. Later, with the development of echo-sounding technologies and war-induced mapping efforts, the variety of sea floor topography became appreciated. Giant submarine mountain chains were recognized where the depth is reduced to 1.7 miles (2.7 km), and these were later interpreted to be oceanic ridges where new oceanic crust is created. Deep-sea trenches with depths exceeding five miles (eight km) were delineated, and later recognized to be subduction zones where oceanic crust sinks back into the mantle. Other anomalous regions of thick oceanic crust (and reduced depths) were recognized, including large oceanic plateaus where excessive volcanism produced thick crust over large regions, and smaller seamounts (or guyots) where smaller, off-ridge volcanism produced isolated submarine mountains. Some of these rose above sea level, were eroded by waves, and grew thick reef complexes as they subsided with the cooling of the oceanic crust. Charles Darwin made such guyots and coral atolls famous in his study of coral reefs of the Pacific Ocean basin.

Pelagic sediments are deposited in the ocean basins and generally form a blanket of sediments draping over preexisting topography. Carbonate rocks produced mainly by the tests of foraminifera and nannofossils may be deposited on the ocean ridges and guyots that are above the carbonate compensation depth (CCD), above which the sea water is saturated with $CaCO_3$, and below which it dissolves in the water. Below this, sediments comprise red clays and radiolarian and diatomaceous ooze. Manganese nodules are scattered about on some parts of the ocean floor.

The abyssal plains are relatively flat, generally featureless parts of the ocean basins where the deep parts of the seafloor topography have been filled in with sediments, forming flat plains, broken occasionally by hills and volcanic islands such as the Bermuda platform, Cape Verde Islands, and the Azores. Some of these submarine plains are quite large, such as the vast 386,100-square mile (1 million-km^2) Angolan abyssal plain in the South Atlantic, and the 1,428,578-square mile (3.7 million-km^2) abyssal plain in the Antarctic Ocean basin. Other abyssal plains are much smaller, such as the 1,003-square mile (2,600-km^2) Alboran Sea in the Mediterranean. Different deep-sea plains may also be characterized and distinguished on the basis of their sediment composition, their geometry, depth, and volume and thickness of the sediments they contain. The deep abyssal areas in the Pacific Ocean are characterized by the presence of more abundant hills or seamounts, which rise up to 0.6 mile (1 km) above the seafloor. For this reason the deep abyssal region of the Pacific is generally referred to as the abyssal hills instead of the abyssal plains. Approximately 80–85 percent of the Pacific Ocean floor lies close to areas with hills and seamounts, making the abyssal hills the most common landform on the surface of the Earth.

Many of the sediments on the deep seafloor (the abyssal plain) are derived from erosion of the continents and carried to the deep sea by turbidity currents or by wind (e.g., volcanic ash) or released from floating ice. Other sediments, known as deep-sea oozes, include pelagic sediments derived from marine organic activity. When small organisms die, such as diatoms in the ocean, their shells sink to the bottom and over time create significant accumulations. Calcareous ooze occurs at low to middle latitudes where warm water favors the growth of carbonate-secreting organisms. Calcareous oozes are not found in water that is more than 2.5–3 miles (4–5 km) deep, because this water is under such high pressure that it contains dissolved CO_2 that dissolves carbonate shells. Siliceous ooze is produced by organisms that use silicon to make their shell structure.

See also OCEANIC PLATEAU; OPHIOLITES; PASSIVE MARGIN; PLATE TECTONICS.

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ocean currents

Like the atmosphere, the ocean is constantly in motion. Ocean currents are defined by the movement paths of water in regular courses, driven by the wind and thermohaline forces across the ocean basins. The wind primarily drives shallow currents, but the Coriolis force systematically deflects them to the right of the atmospheric wind directions in the Northern Hemisphere, and to the left of the prevailing winds in the Southern Hemisphere. Therefore, shallow water currents tend to be oriented about 45° from the predominant wind directions.

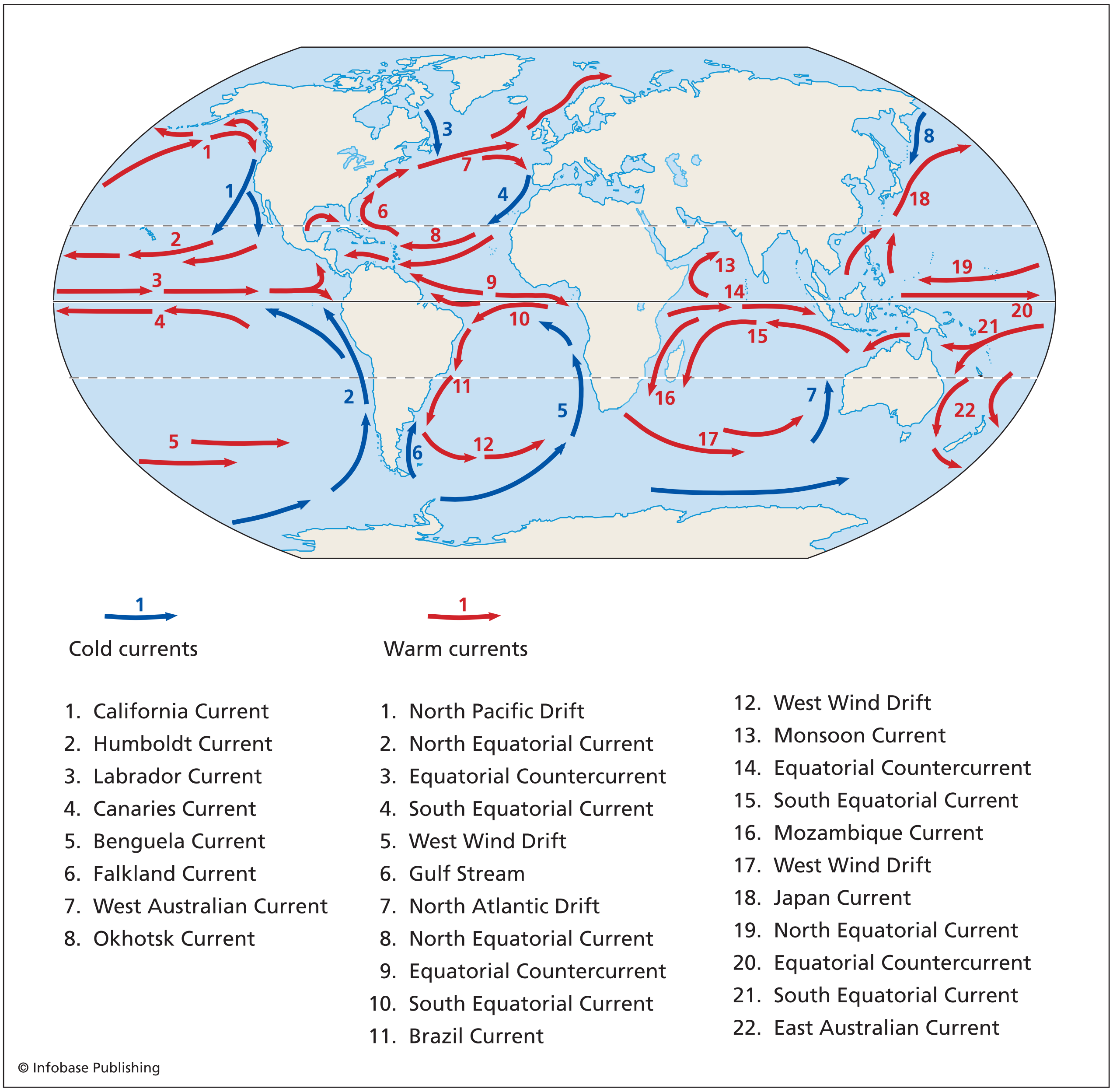
Thermohaline effects, the movement of water driven by differences in temperature and salinity, primarily drive deep-water currents. The Atlantic and Pacific Ocean basins both show a general clockwise rotation in the Northern Hemisphere, and a counterclockwise spin in the Southern Hemisphere, with the strongest currents in the midlatitude sectors. The pattern in the Indian Ocean is broadly similar but seasonally different and more complex because of the effects of the monsoon. Antarctica is bound on all sides by deep water, and has a major clockwise current surrounding it known as the Antarctic Circumpolar Current, lying between 40° and 60° south. This is a strong current, moving at 1.6–5 feet per second (0.5–1.5 m/s) and has a couple of major gyres in it at the Ross Ice Shelf and near the Antarctic Peninsula. The Arctic Ocean has a complex pattern, because it is sometimes ice-covered and is nearly completely surrounded by land with only one major entry and escape route east of Greenland, called Fram Strait. Circulation patterns in the Arctic Ocean are dominated by a slow, 0.4–1.6-inch-per-second (1–4-cm/s) transpolar drift from Siberia to the Fram Strait and by a thermohaline-induced anticyclonic spin known as the Beaufort Gyre that causes ice to pile up on the Greenland and Canadian coasts. Together the two effects in the Arctic Ocean bring numerous icebergs into North Atlantic shipping lanes and send much of the cold deep water around Greenland into the North Atlantic ocean basin.

EKMAN SPIRALS

Ekman spirals are differences in current directions with depth, and form through the turning of water with depth as a result of the Coriolis force. They form because each (infinitesimally thin) layer of the ocean water exerts a frictional drag on the layer below, so that as the top layer moves, the layers below move slightly less with each depth increment. Because the Coriolis force causes moving objects to deflect to the right in the Northern Hemisphere and to the left in the Southern Hemisphere, each successively deeper layer will also be slightly deflected to the right or left of the moving layer above. These effects cause moving water on the surface to be succeeded with depth by progressively slowing and turning particle paths. The Ekman spirals typically extend to about 325 feet (100 m), where the water moves in the direction opposite to that of the surface water that caused the initial flow. The movement of water by Eckman spirals causes a net transport of water to the right of the direction of surface water in the Northern Hemisphere and to the left of the direction of surface water in the Southern Hemisphere. This phenomenon is known as Ekman transport.

GEOSTROPHIC CURRENTS

Some currents in the oceans follow specific horizons on the topographic contours of the ocean basin, staying at the same depth for long distances. These currents in the ocean or atmosphere, in which the horizontal pressure is balanced by the equal but opposite Coriolis force, are known as geostrophic currents. Friction does not affect these currents, which flow to the right of the pressure gradient force along pressure



Map showing major cold and warm ocean currents of the world

isobars in the Northern Hemisphere atmosphere and oceans and to the left in the Southern Hemisphere. In the oceans, geostrophic currents are also known as contour currents, since they follow the bathymetric contours on the seafloor, flowing clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. Downslope currents such as turbidity currents deposit most of the sediments on continental slopes. Since geostrophic or contour currents flow along the bathymetric contours, they rework bottom sediments at right angles to the currents that deposited the sediments. Their work is therefore detectable by examination of paleocurrent indicators that swing from downslope to slope-parallel movement vectors at the top of turbidite and other slope deposits.

COASTAL UPWELLING AND DOWNWELLING CURRENTS

Coastal upwelling is a phenomenon caused by surface winds that blow parallel to the coast, forming ocean surface movements at 90 degrees to the direction of surface winds in Eckman spirals. In many cases, the upper hundred feet or so (few tens of meters) of surface waters move away from the shoreline, forcing a corresponding upwelling of water from depth to replace the water that has moved offshore. This is known as coastal upwelling. Upwelling is most common on the eastern sides of ocean basins, where the surface layer is thin, and near capes and other irregularities in the coastline. Upwelling also occurs away from the coasts along the equator, where surface waters diverge because of the change in sign of the Coriolis force across the equator. Water from depth upwells to replace the displaced surface water.

Zones of coastal and other upwelling, where the water comes from more than 325 feet (100 m) depth, are typically very productive organically, with abundant marine organisms including plants and fish. This is because upwelling coastal waters are rich in nutrients that suddenly become available to benthic and planktonic photic zone organisms.

In contrast to coastal upwelling, coastal downwelling is a phenomenon where winds moving parallel to the coast cause the ocean surface waters to move toward the shoreline, necessitating a corresponding deeper flow from the coast below the shoreward-moving coastal water. Ocean surface currents generally move at right angles to the dominant wind, and move at a velocity of about 2 percent of the wind's. Therefore, onshore winds cause currents to move parallel to the coasts, whereas along shore winds set up currents that move toward or away from the shore.

RAPID CHANGES IN OCEAN CIRCULATION PATTERNS AND CLIMATE CHANGE

Some models of climate change show that patterns of ocean circulation can suddenly change and cause global climate conditions to switch from warm to cold, or cold to warm, over periods of a few decades. Understanding how fast climate can shift from a warm period to a cold, or cold to a warm, is controversial. The record of climate indicators is incomplete and difficult to interpret. Only 18,000 years ago the planet was in the midst of a major glacial interval, and since then global average temperatures have risen 16°F (10°C) and are still rising, perhaps at a recently accelerated rate from human contributions to the atmosphere. Still, recent climate work is revealing that there are some abrupt transitions in the slow warming, in which there are major shifts in some component of the climate, where the shift may happen on scales of 10 years or less.

One of these abrupt transitions seems to affect the ocean circulation pattern in the North Atlantic Ocean, where the ocean currents formed one of two different stable patterns or modes, with abrupt transitions occurring when one mode switches to the other. In the present pattern the warm waters of the Gulf Stream come out of the Gulf of Mexico and flow along the eastern seaboard of the United States, past the British Isles, to the Norwegian Sea. This warm current is largely responsible for the mild climate of the British Isles and northern Europe. In the second mode, the northern extension of the Gulf Stream is weakened by a reduction in salinity of surface waters from sources at high latitudes in the North Atlantic. The fresher water has a source in increased melting from the polar ice shelf, Greenland, and northern glaciers. With less salt, seawater is less dense, and is less able to sink during normal wintertime cooling.

Studies of past switches in the circulation modes of the North Atlantic reveal that the transition from mode 1 to mode 2 can occur over a period of only five to 10 years. These abrupt transitions are apparently linked to increase in the release of icebergs and freshwater from continental glaciers, which upon melting contribute large volumes of freshwater into the North Atlantic, systematically reducing the salinity. The Gulf Stream presently seems on the verge of failure, or of switching from mode 1 to mode 2, and historical records show that this switch can be very rapid. If this predicted switch occurs, northern Europe and the United Kingdom may experience a significant and dramatic cooling of their climate, instead of the warming many fear.

See also El Niño and the Southern Oscillation (ENSO); energy in the Earth system; hydrosphere; ocean basin; oceanography; pelagic, nektonic, planktonic; thermohaline circulation.

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oceanic plateau Regions of anomalously thick oceanic crust and topographically high seafloor are known as oceanic plateaus. Many have oceanic crust that is 12.5–25 miles (20–40 km) thick, and rise thousands of meters above surrounding oceanic crust of normal thickness. The Caribbean ocean floor represents one of the best examples of an oceanic plateau, with other major examples including the Ontong-Java Plateau, Manihiki Plateau, Hess Rise, Shatsky Rise, and Mid-Pacific Mountains. All of these oceanic plateaus contain thick piles of volcanic and subvolcanic rocks representing huge outpourings of lava; most erupted in a few million years. They typically do not show the magnetic stripes that characterize normal oceanic crust produced at oceanic ridges, and are thought to have formed when mantle plume heads reached the base of the lithosphere, releasing huge amounts of magma. Some oceanic plateaus have such large volumes of magma that the total magmatic flux in the plateaus would have been similar to or larger than all of the magma erupted at the mid-ocean ridges during the same interval. The Caribbean seafloor preserves 5–7.5-mile- (8–21-km-) thick oceanic crust formed before about 85 million years ago in the eastern Pacific Ocean. Plate tectonics transported this unusually thick ocean floor eastward, where pieces of the seafloor collided with South America as it passed into the Atlantic Ocean. Pieces of the Caribbean oceanic crust are now preserved in Colombia, Ecuador, Panama, Hispaniola, and Cuba, and some scientists estimate that the Caribbean oceanic plateau may have once been twice its present size. An accompanying vast outpouring of lava would have been associated with significant outgassing, with possible consequences for global climate and evolution.

The western Pacific Ocean basin contains several large oceanic plateaus, including the 20-mile- (32-km-) thick crust of the Ontong-Java Plateau, which is the largest outpouring of volcanic rocks on the planet. The Ontong-Java Plateau is the largest igneous province in the world not associated with the oceanic-ridge spreading-center network, covering an area roughly the size of Alaska (9,300,000 square miles, or 15,000,000 km^2). The plateau is located northeast of Papua New Guinea and the Solomon Islands in the southwest Pacific Ocean, centered on the equator at 160°E longitude. Most of the plateau formed about 122 million years ago in the Cretaceous period, probably as a result of a mantle plume rising to the surface and causing massive amounts of volcanism over a geologically short interval, likely lasting only about a million years. Smaller amounts of volcanic material erupted later, at about 90 million years ago. Together, these events formed a lava plateau that is 20 miles (32 km) thick. The amount of volcanic material produced to form the plateau is estimated to be approximately the same as that erupted from the entire global ocean-ridge spreading-center system in the same period. Such massive amounts of volcanism cause worldwide changes in climate and ocean temperatures and typically have great impacts on the biosphere. Sea levels rose by more than 30 feet (9 m) in response to this volcanic outpouring. The gases released during these eruptions are estimated to have raised average global temperatures by 23°F (13°C). Perhaps more remarkably, the Ontong-Java Plateau is but one of many Cretaceous oceanic plateaus in the Pacific, suggesting that the Cretaceous was characterized by a long-standing eruption of massive amounts of deeply derived magma. Some geologists have suggested that events like this relate to major mantle overturn events, when plumes dominate heat loss from the Earth instead of oceanic-ridge spreading, as in the present plate mosaic.

The plateau is thought to be composed largely of basalt, based on limited sampling, deep-sea drilling, and seismic velocities. A covering by a thick veneer of sediments, exceeding thousands of feet (a kilometer or more) in most places, presents great difficulties in trying to sample the plateau. The plateau is colliding with the Solomon trench, but thick oceanic plateaus like the Ontong-Java are generally unsubductable. When oceanic plateaus are attempted to be subducted,

Map of the world showing major flood basalt regions, including oceanic plateaus they typically get accreted to the continents, leading to continental growth.

See also African geology; large igneous provinces, flood basalt.

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oceanography The study of the physical, chemical, biological, and geological aspects of the ocean basins is oceanography. Oceanographers have begun using an Earth system science approach to study the oceans, with the appreciation that many of the different systems are related, and changes in the biological, chemical, physical, or geological conditions will result in changes in the other systems and also influence other Earth systems such as the atmosphere and climate. The oceans contain important geological systems, since the ocean basins are the places where oceanic crust is both created at mid-ocean ridges and destroyed at deep-sea trenches. Being topographic depressions, they are repositories for many of the sediments eroded from the continents and carried by rivers and the wind to be deposited in submarine settings. Seawater is the host of much of the life on Earth and also holds huge quantities of dissolved gases and chemicals that buffer the atmosphere, keeping global temperatures and climate hospitable for humans. Energy is transferred around the planet in ocean currents and waves, which interact with land, eroding or depositing shoreline environments. Being host to some of the planet's largest and most diverse biota, the oceans may hold the key to feeding the planet. Mineral resources are also abundant on the seafloor, many formed at the interface between hot volcanic fluids and cold seawater, forming potentially economically important reserves of many minerals.

The oceans cover two-thirds of the Earth's surface, yet scientists have explored less of the ocean's depths and mysteries than the surfaces of several nearby planets. The oceans have hindered migration of peoples and biota between distant continents, yet paradoxically now serve as a principal means of transportation. Oceans provide us with incredible mineral wealth and renewable food and energy sources, yet also breed devastating hurricanes. Life may have begun on Earth in environments simulated by hot volcanic events on the seafloor, and marine biologists are exploring the diverse and unique fauna that can still be found living in deep dark waters around similar vents today.

Ocean basins have continually opened and closed on Earth, and the continents have alternately been swept into large single supercontinents and then broken apart by the formation of new ocean

USNS *Bowditch*, a U.S. Navy T-AGS 60 Class oceanographic survey ship *(U.S. Navy photo)*

Japanese research vessel *Natsushima,* support ship for the Shinkai subs *(Science Source/Photo Researchers, Inc.)*

basins. The appearance, evolution, and extinction of different life-forms is inextricably linked to the opening and closing of ocean basins, partly through the changing environmental conditions associated with the changing distribution of oceans and continents.

Early explorers slowly learned about ocean currents and routes to distant lands, and some dredging operations revealed huge deposits of metals on the seafloor. Tremendous leaps in our understanding of the structure of the ocean basin seafloor were acquired during surveying for the navigation of submarines and detection of enemy submarines during World War II. Magnetometers towed behind ships and accurate depth measurements provided data that led to the formulation of the hypothesis of seafloor spreading, which added the oceanic counterpart to the idea of continental drift. The plate tectonic paradigm later unified these two theories.

Ocean circulation is responsible for much of the world's climate. For instance, mild foggy winters in London are caused by warm waters from the Gulf of Mexico flowing across the Atlantic via the Gulf Stream to the coast of the British Isles. Large variations in ocean and atmospheric circulation patterns in the Pacific lead to alternating wet and dry climate conditions known as El Niño and La Niña. These variations affect Pacific regions most strongly, but are felt throughout the world. Other more dramatic movements of water include the sometimes devastating tsunamis initiated by earthquakes, volcanic eruptions, and giant submarine landslides.

One of the most tragic tsunamis in recent history occurred on December 26, 2004, following a magnitude 9.0 earthquake off the coast of northern Sumatra in the Indian Ocean. The earthquake was the largest since the 1964 magnitude 9.2 event in southern Alaska and released more energy than all the earthquakes on the planet in the last 25 years combined. During this catastrophic earthquake, a segment of the seafloor the size of the state of California, lying above the Sumatra subduction zone trench, suddenly moved upward and seaward by more than 30 feet (9 m). The sudden displacement of this volume of undersea floor displaced a huge amount of water and generated the most destructive tsunami known in recorded history. Within minutes of the initial earthquake a mountain of water more than 100 feet (30 m) high was ravaging northern Sumatra, sweeping into coastal villages and resort communities with a fury that crushed all in its path, removing buildings and vegetation, and in many cases eroding shoreline areas down to bedrock, leaving no traces of the previous inhabitants or structures. Similar scenes of destruction and devastation rapidly moved up the coast of nearby Indonesia, where residents and tourists were enjoying a holiday weekend. Firsthand accounts of the catastrophe reveal similar scenes of horror where unsuspecting tourists and residents were enjoying themselves in beachfront playgrounds, resorts, and villages, and reacted as large breaking waves appeared off the coast. Many moved toward the shore to watch the high surf with interest, then ran in panic as the sea rapidly rose beyond expectations, and walls of water engulfed entire beachfronts, rising above hotel lobbies, and washing through towns with the force of Niagara Falls. In some cases the sea retreated to unprecedented low levels before the waves struck, causing many people to move to the shore to investigate the phenomenon; in other cases, the sea waves simply came crashing inland without warning. Buildings, vehicles, trees, boats and other debris were washed along with the ocean waters, forming projectiles that smashed at speeds of up to 30 miles per hour (50 km/hr) into other structures, leveling all in their paths, and killing more than a quarter million people.

Another tragic tsunami in history was generated by the eruption of the Indonesian volcano Krakatau in 1883. When Krakatau erupted, it blasted out a large part of the center of the volcano, and seawater rushed in to fill the hole. This seawater was immediately heated and it exploded outward in a steam eruption and a huge wave of hot water. The tsunami generated by this eruption reached more than 120 feet (36.5 m) in height and killed an estimated 36,500 people in nearby coastal regions. In 1998 a catastrophic 50-foot- (15-m-) high wave unexpectedly struck Papua New Guinea, killing more than 2,000 people and leaving more than 10,000 homeless.

Rich mineral deposits fill the oceans—oil and gas are on the continental shelves and slopes, and metalliferous deposits form near mid-ocean ridge vents. Much of the world's wealth of manganese, copper, and gold lies on the seafloor. The oceans also yield rich harvests of fish, and care must be taken to not deplete this source. Sea vegetables are growing in popularity, and their use may help alleviate the growing demand for space in fertile farmland. The oceans may offer the world a solution to growing energy and food demands resulting from a rapidly growing population. New life-forms are constantly being discovered in the depth of the oceans, and precautions must be taken to understand these creatures before any changes people make to their environment cause them to perish forever.

HISTORY OF EXPLORATION OF THE WORLD'S OCEAN BASINS

The earliest human exploration of the oceans is poorly known, but pictures of boats on early cave drawings in Norway illustrate Viking-style ocean vessels known to be used by the Vikings centuries later. Other rock drawings around the world show dugout canoes, boats made of reeds, bark, and animal hides. Early migrations of humans must have utilized boats to move from place to place. For instance, analysis of languages and of genetics shows that the Polynesians moved south from China into southeast Asia and Polynesia, then somehow made it, by sea, all the way to Madagascar off the east coast of Africa. Other oceanic migrations include the colonization of Europe by Africans about 10,000 years ago, explorations and trade around and out of the Mediterranean by the Phoenicians about 3,000 years ago, and the colonization of North America by the Siberians and Vikings. Ming Dynasty ocean explorations in the early 1400s were massive, involving tens of thousands of sailors on 317 ships. The Chinese ships were huge, including as many as nine masts more than 444 feet (135 m) in length and 180 feet (55 m) in width. The Chinese mounted these expeditions to promote Chinese culture, society, and technology but did not contribute significantly to understanding the oceans.

The first European to reach North America was probably Leif Eriksson, who, in the year 1,000, landed at L'Anse-aux Meadows in the Long Range Peninsula of Newfoundland, after becoming lost on his way from Greenland to Norway. The Vikings established a temporary settlement in Newfoundland, and there are some speculations of further explorations by the Vikings to places as far south as New England and Narragansett Bay in Rhode Island. Their colonies disappeared during the Dark Ages, probably as a result of a global climate cooling trend that turned previously arable lands into arctic tundra.

Ptolemy (in the year 140) published maps of Europe's coastline that were largely inaccurate and took many years of ocean exploration to correct. The Greeks and Islamic explorers had made great strides in understanding the geography of the world centered on the Mediterranean Sea and Arabian Peninsula, and the records of these explorations eventually made it into European hands, where this knowledge was used for further explorations. The Portuguese, most notably Prince Henry the Navigator (1392–1460), were the most avid explorers of the Atlantic, exploring northwest Africa and the Azores in the early 1400s. In the late 1400s, Vasco da Gama (1460–1524) made it to southern Africa and eventually around the Cape of Good Hope, past Madagascar, and all the way to India in 1498. These efforts initialized economically important trade routes between Portugal and India, building the powerful Portuguese Empire. The timing was perfect for establishment of ocean trade routes, as the long-used overland Silk Roads had become untenable and dangerous with the collapse of the Mongol Empire and the Turk conquest of Constantinople (Istanbul) in 1453.

In the late 15th and early 16th centuries, many ocean exploration expeditions were mounted as a precursor to more widespread use of the oceans for transportation. In 1492, Christopher Columbus sailed from Spain to the east coast of North America, and from the late 1400s to 1521 Ferdinand Magellan sailed around the world, including a crossing of the Pacific Ocean, followed by Sir Francis Drake of England. Later, Henry Hudson explored North American waters, including attempts to find a northwest passage between the Atlantic and Pacific. During the 1700s, Captain James Cook made several voyages in the Pacific and coastal waters of western North America, improving maps of coastal and island regions.

The early explorations of the oceans were largely concerned with navigation and determining the positions of trade routes, coastlines, and islands. Later, sea-going expeditions aimed at understanding the physical, chemical, biological, and geological conditions in the ocean were mounted. In the late 1800s the British Royal Society sponsored the world's most ambitious scientific exploration of the oceans ever, the voyage of the H.M.S. *Challenger*. The voyage of the *Challenger* in 1872–76 established for the first time many of the basic properties of the oceans and set the standard for the many later expeditions.

Ocean exploration today is led by American teams based at several universities, Scripps Institute of Oceanography, and Woods Hole Oceanographic Institute, where the deep submersible Alvin is based and from where many oceanographic cruises are coordinated. The Ocean Drilling Program (formerly the Deep-Sea Drilling Project) has amassed huge quantities of data on the sediments and volcanic rocks deposited on the ocean floor, as well as information about biology, climate, chemistry, and ocean circulation. Many other nations, including Japan, China, France, and Russia have mounted ocean exploration campaigns, with a trend toward international cooperation in understanding the evolution of the ocean basins.

See also OCEAN BASIN; OCEAN CURRENTS; OPHIOLITES; PLATE TECTONICS.

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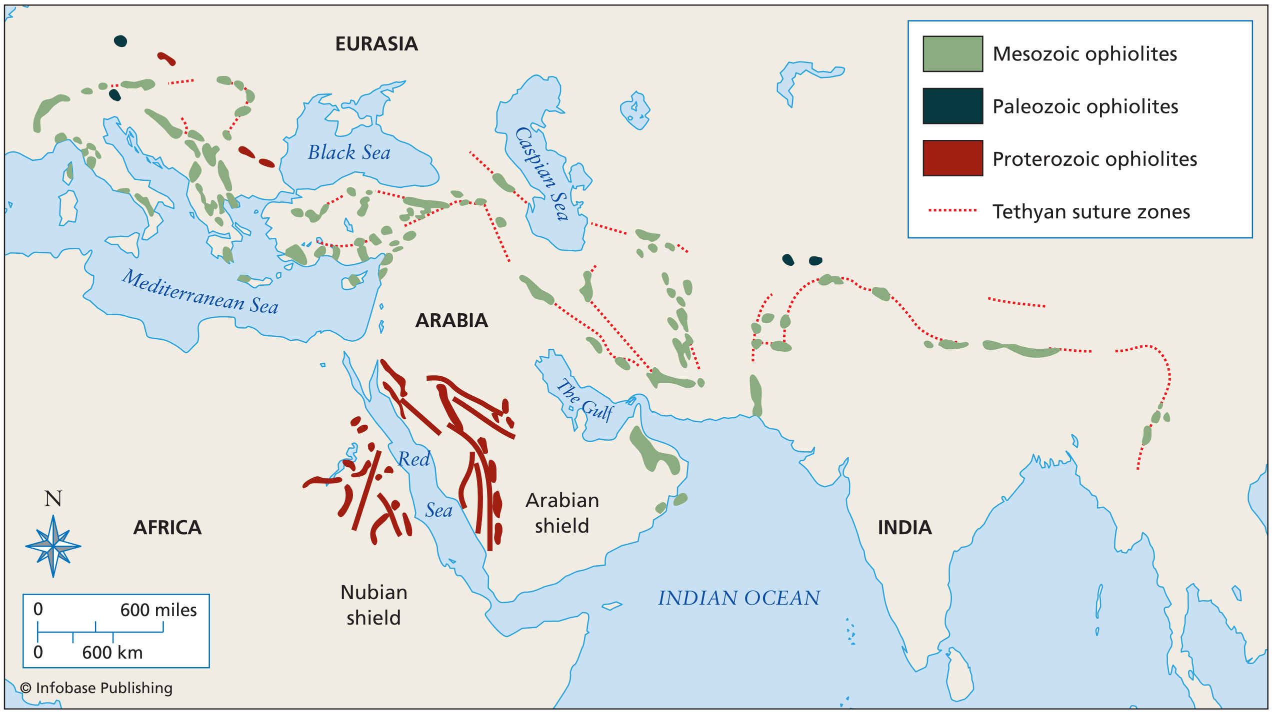
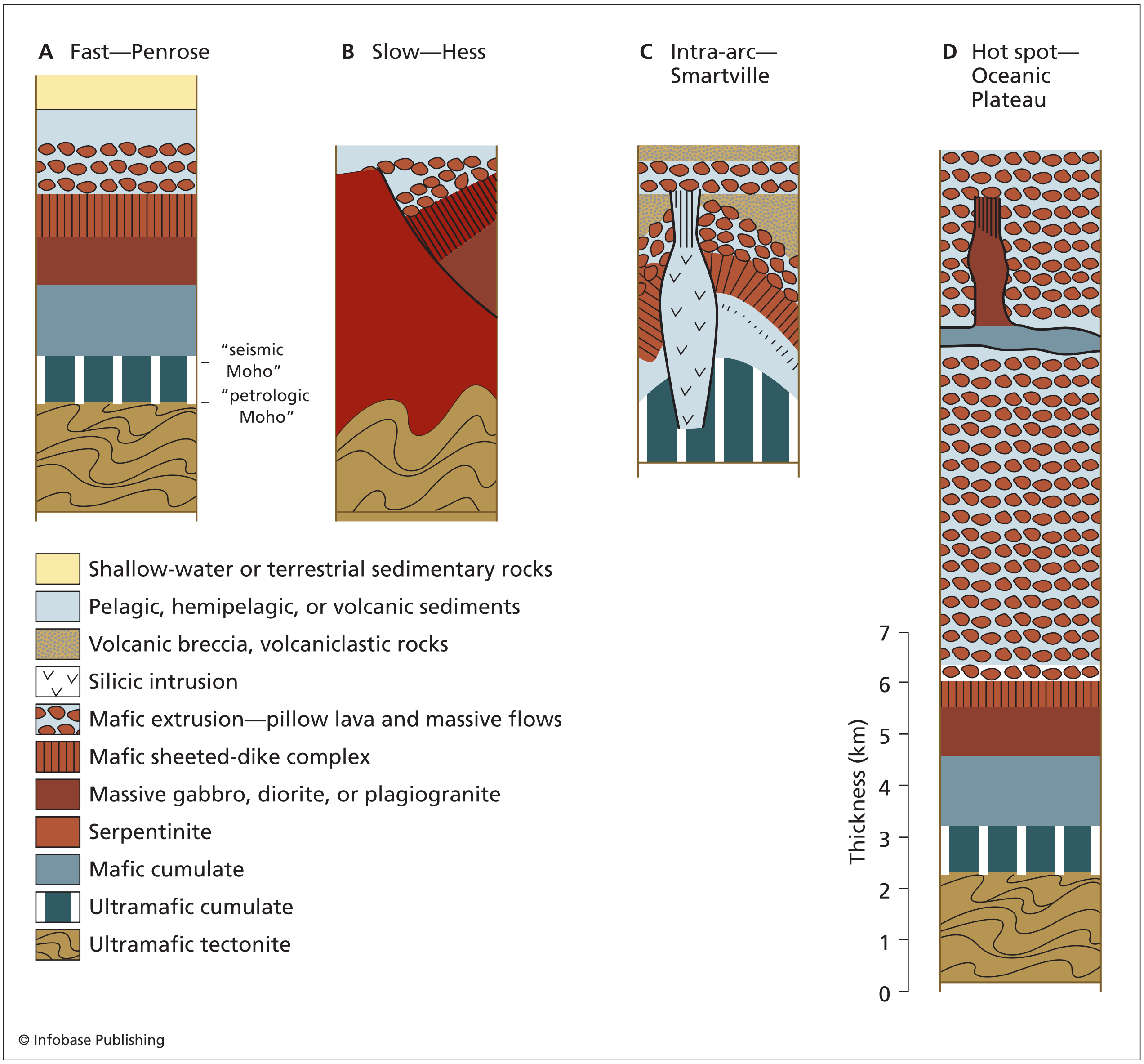
ophiolites A distinctive group of rocks that includes basalt, diabase, gabbro, and peridotite, the ophiolites may also be associated with chert, metalliferous sediments (umbers), trondhjemite, diorite, and serpentinite. Many ophiolites are altered to serpentinite, chlorite, albite, and epidote-rich rocks, possibly by hydrothermal seafloor metamorphism. German geologist G. Steinman introduced the term in 1905 for a tripartite assemblage of rocks, including basalt, chert, and serpentinite, that he recognized as a common rock association in the Alps. Most ophiolites form in an ocean-floor environment, including at mid-ocean ridges, in back-arc basins, in extensional forearcs, or within arcs. Ophiolites are detached from the oceanic mantle and have been thrust upon continental margins during the closure of ocean basins. Lines of ophiolites decorate many sutures around the world, marking places where oceans have closed. In the 1960s and 1970s much research focused on defining a type of ophiolite succession that became known as the Penrose-type of ophiolite. More recent research has revealed that the variations between individual ophiolites are as significant as any broad similarities between them.

A classic Penrose-type of ophiolite is typically three to nine miles (5–15 km) thick and if complete, consists of the following sequence from base to top, with a fault marking the base of the ophiolite. The lowest unit in some ophiolites is an ultramafic rock called lherzolite, consisting of olivine + clinopyroxene + orthopyroxene, generally interpreted to be fertile, undepleted mantle. The base of most ophiolites



Map showing distribution of ophiolites in the Tethyan orogenic belt, showing the location of Proterozoic, Paleozoic, and Mesozoic ophiolites



Cross sections through typical ophiolites, including different types of ophiolites produced at slow, intra-arc, and hotspot types of tectonic settings

consists of an ultramafic rock known as harzburgite, consisting of olivine + orthopyroxene (± chromite), often forming strongly deformed or transposed compositional layering, forming a distinctive rock known as harzburgite tectonite. In some ophiolites, harzburgite overlies lherzolite. The harzburgite is generally interpreted to be the depleted mantle from which overlying mafic rocks were derived, and the deformation is related to the overlying lithospheric sequence flowing away from the ridge along a shear zone within the harzburgite. The harzburgite sequence may be six miles (10 km) or more thick in some ophiolites, such as the Semail ophiolite in Oman, and the Bay of Islands ophiolite in Newfoundland.

Resting above the harzburgite is a group of rocks that were crystallized from a magma derived by partial melting of the harzburgite. The lowest unit of these crustal rocks includes crystal cumulates of pyroxene and olivine, forming distinctive layers of pyroxenite, dunite, and other olivine + clinopyroxene + orthopyroxene peridotites, including wehrlite, websterite, and pods of chromite + olivine. The boundary between these rocks (derived by partial melting and crystal fractionation) and those below from which melts were extracted is one of the most fundamental boundaries in the crust, known as the Moho, or base of the crust, named after the Yugoslavian seismologist Andrija Mohorovičić, who noted a fundamental seismic boundary beneath the continental crust. In this case, the Moho is a chemical boundary, without a sharp seismic discontinuity. A seismic discontinuity occurs about 1,500–1,600 feet (half a kilometer) higher than the chemical Moho in ophiolites.

The layered ultramafic cumulates grade upward into a transition zone of interlayered pyroxenite and plagioclase-rich cumulates, then into an approximately half-mile (1 km) thick unit of strongly layered gabbro. Individual layers within this thin unit may include gabbro, pyroxenite, and anorthosite. The layered gabbro is succeeded upward by one to three miles (2–5 km) of isotropic gabbro, which is generally structureless but may have a faint layering. The layers within the isotropic gabbro in some ophiolites define a curving trajectory, interpreted to represent crystallization along the walls of a paleomagma chamber. The upper part of the gabbro may contain many xenoliths of diabase and pods of trondhjemite (plagioclase plus quartz) and may be cut by diabase dikes.

The next highest unit in a complete, Penrose-style ophiolite is typically a sheeted dike complex, consisting of a 0.3–1.25-mile- (0.5–2 km-) thick complex of diabasic, gabbroic, to silicic dikes that show mutually intrusive relationships with the underlying gabbro. In ideal cases, each diabase dike intrudes into the center of the previously intruded dike, forming a sequence of dikes that have chilled margins developed only on one side. These dikes are said to exhibit one-way chilling. In most real ophiolites, examples of one-way chilling may be found, but statistically the one-way chilling may only show directional preference in 50–60 percent of cases.

The sheeted dikes represent magma conduits that fed basaltic flows at the surface. These flows are typically pillowed, with lobes and tubes of basalt forming bulbous shapes distinctive of underwater basaltic volcanism. The pillow basalt section is typically 0.3–0.6 mile (0.5–1 km) thick. Chert and sulfide minerals commonly fill the interstices between pillows.

Deep-sea sediments, including chert, red clay, in some cases carbonates, or sulfide layers, overlie many ophiolites. Many variations are possible, depending on tectonic setting (e.g., conglomerates may form in some settings) and age (e.g., siliceous biogenic oozes and limestones would not form in Archean ophiolites, before the life-forms that contribute their bodies developed).

PROCESSES OF OPHIOLITE AND OCEANIC-CRUST FORMATION

The sequences of rock types described above result from a specific set of processes that occurred along the oceanic-spreading centers where the ophiolites formed. As the mantle convects and the asthenosphere upwells beneath mid-ocean ridges, the mantle harzburgites undergo partial melting of 10–15 percent in response to the decreasing pressure. The melts derived from the harzburgites rise to form a magma chamber beneath the ridge, forming the crustal section of the oceanic crust. As the magma crystallizes, the densest crystals gravitationally settle to the bottom of the magma chamber, forming layers of ultramafic and higher mafic cumulate rocks. Above the cumulate a gabbroic fossil magma chamber forms, typically with layers defined by varying amounts of pyroxene and feldspar crystals. In many examples the layering in ophiolites is parallel to the fossil margins of the magma chamber. An interesting aspect of the magma chamber is that periodically, new magma is injected into the chamber, changing the chemical and physical dynamics. These new magmas are injected during extension of the crust so the magma chamber may effectively expand infinitely if the magma supply is continuous, as in fast-spreading ridges. In slow-spreading ridges the magma chamber may completely crystallize before new batches of melt are injected.

As extension occurs in the oceanic crust, dikes of magma shoot out of the gabbroic magma chamber, forming a diabasic (fine-grained, rapidly cooled magma with the same composition as gabbro) sheeted dike complex. The dikes tend to intrude along the weakest, least crystallized part of the previous dike, which is usually in the center of the last dike to intrude. In this way, each dike intrudes the center of the previous dike, forming a sheeted dike complex characterized by dikes that have only one chill margin, most of which face in the same direction.

Many of the dikes reach the surface of the seafloor where they feed basaltic lava flows. Basaltic lava flows on the seafloor are typically in the form of bulbous pillows that stretch out of magma tubes, forming the distinctive pillow lava section of ophiolites. Seafloor metamorphism typically alters the top of the pillow lava section, including having deposits of black smoker-type hydrothermal vents. Sediments deposited on the seafloor overlie the pillow lavas. If the oceanic crust forms above the calcium carbonate compensation depth, the lowermost sediments may be calcareous. These would be succeeded by siliceous oozes, pelagic shales, and other sediments as the seafloor cools, subsides, and moves away from the mid-ocean ridge. A third sequence of sediments may be found on the ophiolites. These would include sediments shed during detachment of the ophiolite from the seafloor basement and its thrusting or emplacement onto the continental margin.

The type of sediments deposited on ophiolites may have been very different in some of the oldest ophiolites that formed in the Precambrian.

For instance, in the Proterozoic and especially the Archean, organisms that produce the carbonate and siliceous oozes would not be present, as the organisms that produced these sediments had not yet evolved.

There is considerable variation in the classical ophiolite sequence described above, as first formally defined by the participants of a Penrose conference on ophiolites in 1972. First, because most ophiolite sequences are deformed and metamorphosed, recognizing many of the primary magmatic units, especially sheeted dikes, is difficult. Deformation associated with emplacement typically causes omission of some or several sections of the complete sequence, and repetition of others along thrust faults. Therefore the adjectives *metamorphosed, partial,* and *dismembered* often serve as prefixes to descriptions of individual ophiolites. The thickness of individual units also varies considerably—some may be totally absent, and different units may be present in specific examples. Similar variations are noted from the modern seafloor and island arc systems, likely settings for the formation of ophiolites. Most ophiolites are interpreted to be fragments of the ocean floor generated at mid-ocean ridges, but the thickness of the modern oceanic crustal section is about 4 miles (7 km), whereas the equivalent units in ophiolites average about 1.8–3.1 miles (3–5 km).

Some of the variations relate to the variety of tectonic environments in which ophiolites form. Results from the Ocean Drilling Program, in which the oceanic crust has been drilled in a number of locations, have helped geologists to determine which units in what thickness are present in different sections of oceanic crust. Fast-spreading centers such as the East Pacific Rise typically show the complete ophiolite sequence, whereas slow-spreading centers such as the Mid-Atlantic Ridge may be incomplete, in some cases entirely lacking the magmatic section. Other ophiolites may form at or near transform faults, in island arcs, back-arc basins, forearcs, or above plumes.

THE WORLD'S OLDEST OPHIOLITE

Prior to 2001, no complete Phanerozoic-like ophiolite sequences had been recognized from Archean rock sequences around the world, leading some workers to the conclusion that no Archean ophiolites or oceanic crustal fragments are preserved. These ideas were challenged by the discovery of a complete 2.5 billion-year-old ophiolite sequence in the North China craton. This remarkable rock sequence includes chert and pillow lava, a sheeted dike complex, gabbro and layered gabbro, cumulate ultramafic rocks, and a suite of strongly deformed mantle harzburgite tectonites, all complexly deformed in a series of fault blocks. The mantle rocks include a distinctive type of intrusion with metallic chrome nodules called a podiform chromite deposit, known to form only in oceanic crust.

Well-preserved black smoker chimney structures in metallic sulfide deposits have also been discovered in some sections of the Dongwanzi ophiolite belt, and these ancient seafloor hydrothermal vents are among the oldest known. Deep-sea hydrothermal vents host the most primitive thermophyllic, chemosynthetic, sulfate-reducing organisms known, believed to be the closest relatives of the oldest life on Earth, with similar vents having possibly provided nutrients and protected environments for the first organisms. These vents are associated with some unusual microscale textures that may be remnants of early life-forms, most likely bacteria. These ancient fossils provide tantalizing suggestions that early life may have developed and remained sheltered in deep-sea hydrothermal vents until surface conditions became favorable for organisms to inhabit the land.

Archean oceanic crust was possibly thicker than Proterozoic and Phanerozoic counterparts, resulting in accretion predominantly of the upper basaltic section of oceanic crust. The crustal thickness of Archean oceanic crust may in fact have resembled modern oceanic plateaus. If this were the case, complete Phanerozoic-like ophiolite sequences would have been very unlikely to be accreted or obduced during Archean orogenies. In contrast, only the upper, pillow lava–dominated sections would likely be accreted. Remarkably, Archean greenstone belts contain an abundance of tectonic slivers of pillow lavas, gabbros, and associated deep-water sedimentary rocks. The observation that Archean greenstone belts have such an abundance of accreted ophiolitic fragments compared to Phanerozoic orogens suggests that thick, relatively buoyant, young Archean oceanic lithosphere may have had a rheological structure favoring delamination of the uppermost parts during subduction and collisional events.

See also AFRICAN GEOLOGY; ARABIAN GEOLOGY; ASIAN GEOLOGY; CONVERGENT PLATE MARGIN PROCESSES; DIVERGENT PLATE MARGIN PROCESSES; OROGENY.

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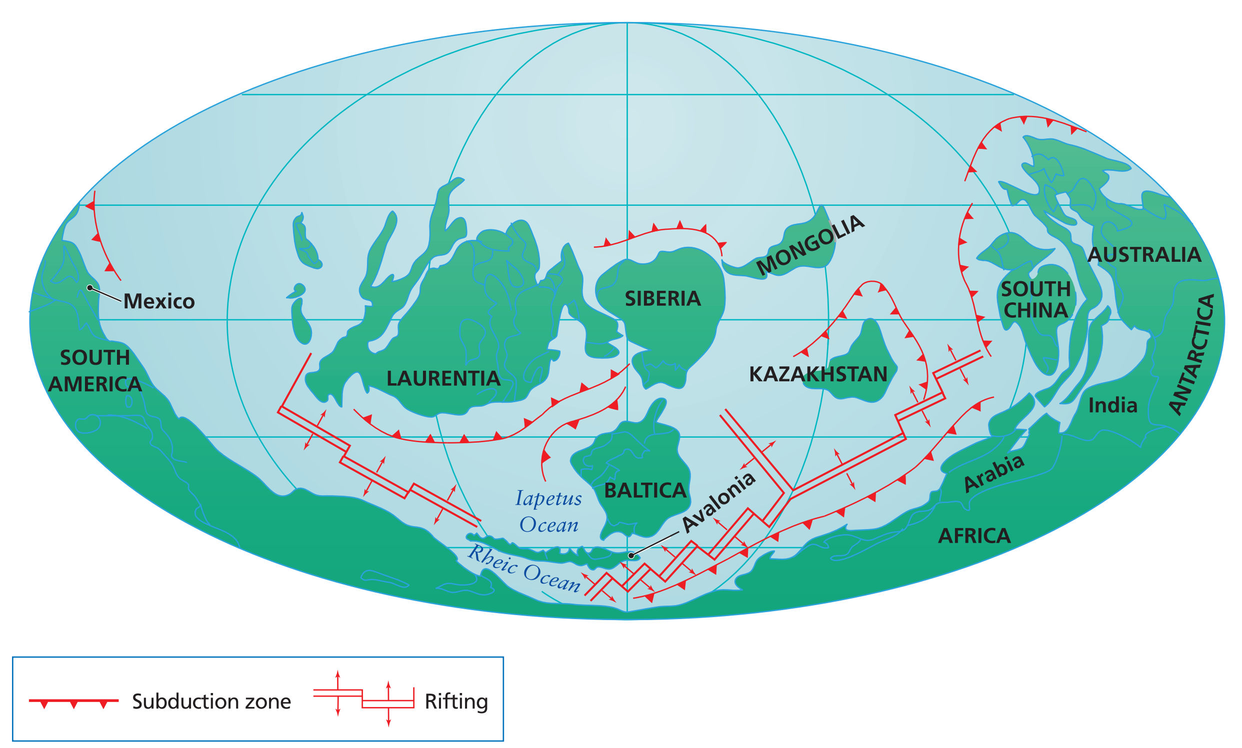
Ordovician The Ordovician is the second period of the Paleozoic Era and refers to the corresponding rock series, falling between the Cambrian and the Silurian. Commonly referred to as the age of marine invertebrates, the base of the Ordovician is defined on the Geological Society of America time scale (1999) as 490 million years ago, and the top or end of the Ordovician is defined at 444 million years ago. Charles Lapworth named the period, in 1879, after the Ordovices, a Celtic tribe that inhabited the Arenig-Bala area of northern Wales, where rocks of this series are well exposed.

By the Early Ordovician, North America had broken away from the supercontinent of Gondwana that amalgamated during the latest Precambrian and early Cambrian Period. It was surrounded by shallow water passive margins, and being at equatorial latitudes, these shallow seas were well suited for the proliferation of marine life-forms. The Iapetus Ocean separated what is now the east coast of North America from the African and South American segments of the remaining parts of Gondwana. By the Middle Ordovician, convergent tectonics brought an island arc system to the North American margin, initiating the Taconic orogeny as an arc/continent collision. This was followed by a sideways sweep of parts of Gondwana past the North American margin, leaving fragments of Gondwana attached to the modified eastern margin of North America.

During much of the Ordovician, carbonate sediments produced by intense organic productivity covered shallow epeiric seas in the tropical regions, including most of North America. This dramatic increase in carbonate sedimentation reflects a combination of tectonic activities that brought many low-lying continental fragments into the Tropics, high–sea level stands related to the breakup of Gondwana, and a sudden increase in the number of different organisms that started to use calcium carbonate to build their skeleton or shell structures.

Marine life included diverse forms of articulate brachiopods, communities of echinoderms such as the crinoids or sea lilies, and reef-building stro-



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Ordovician paleogeography showing the distribution of continents approximately 500 million years ago

Two Ordovician trilobite fossils from the Wolchow River in Russia. Left is *Cerauinella ingrica* (12.5 cm long), right is *Pseudobasilica lawrowi* *(François Gohier/Photo Researchers, Inc.)*

matoporoids, rugose and tabulate corals. Trilobites roamed the shallow seafloors, and many forms emerged. The Ordovician saw rapid diversification and wide distribution of several planktonic and pelagic faunas, especially the graptolites and conodonts, which form useful index fossils for this period. Nautiloids floated across the oceans and some attained remarkably large sizes, reaching up to more than 10 feet (several meters) across. Fish fossils are not common from Ordovician deposits, but some primitive armored types may have been present. The end of the Ordovician is marked by a marine extinction event, apparently caused by rapid cooling of the shallow seas, perhaps related to continental glaciation induced by tectonic plate movements. The end-Ordovician extinction is one of the greatest of all Phanerozoic time. About half of all species of brachiopods and bryozoans died off, and more than 100 other families of marine organisms disappeared forever.

The cause of the mass extinction at the end of the Ordovician appears to have been largely tectonic. The major landmass of Gondwana had been resting in equatorial regions for much of the Middle Ordovician, but migrated toward the South Pole at the end of the Ordovician. This caused global cooling and glaciation, lowering sea levels from the high stand they had been resting at for most of the Cambrian and Ordovician. The combination of cold climates with lower sea levels, leading to a loss of shallow shelf environments for habitation, probably was enough to cause the mass extinction at the end of the Ordovician.

See also North American geology; Paleozoic.

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origin and evolution of the Earth and solar system

Understanding the origin of the Earth, planets, Sun, and other bodies in the solar system is a fundamental yet complex problem that has intrigued scientists and philosophers for centuries. Most of the records from the earliest history of the Earth have been lost to tectonic reworking and erosion, so most information about the formation of the Earth and solar system comes from the study of meteorites, the Earth's Moon, and observations of the other planets and interstellar gas clouds. In addition, isotope geochemistry can be used to understand some of the conditions on the early Earth.

The solar system displays many general trends with increasing distance from the Sun, and systematic changes like these imply that the Sun did not gravitationally capture planets, but rather the Sun and planets formed from a single event that occurred about 4.6 billion years ago. The nebular theory for the origin of the solar system suggests that a large spinning cloud of dust and gas formed and began to collapse under its own gravitational attraction. As it collapsed, it began to spin faster to conserve angular momentum (much like ice skaters spin faster when they pull their arms in to their chests) and eventually formed a disk. Collisions between particles in the disk formed protoplanets and a protosun, which then had larger gravitational fields than surrounding particles and began to sweep up and accrete loose particles.

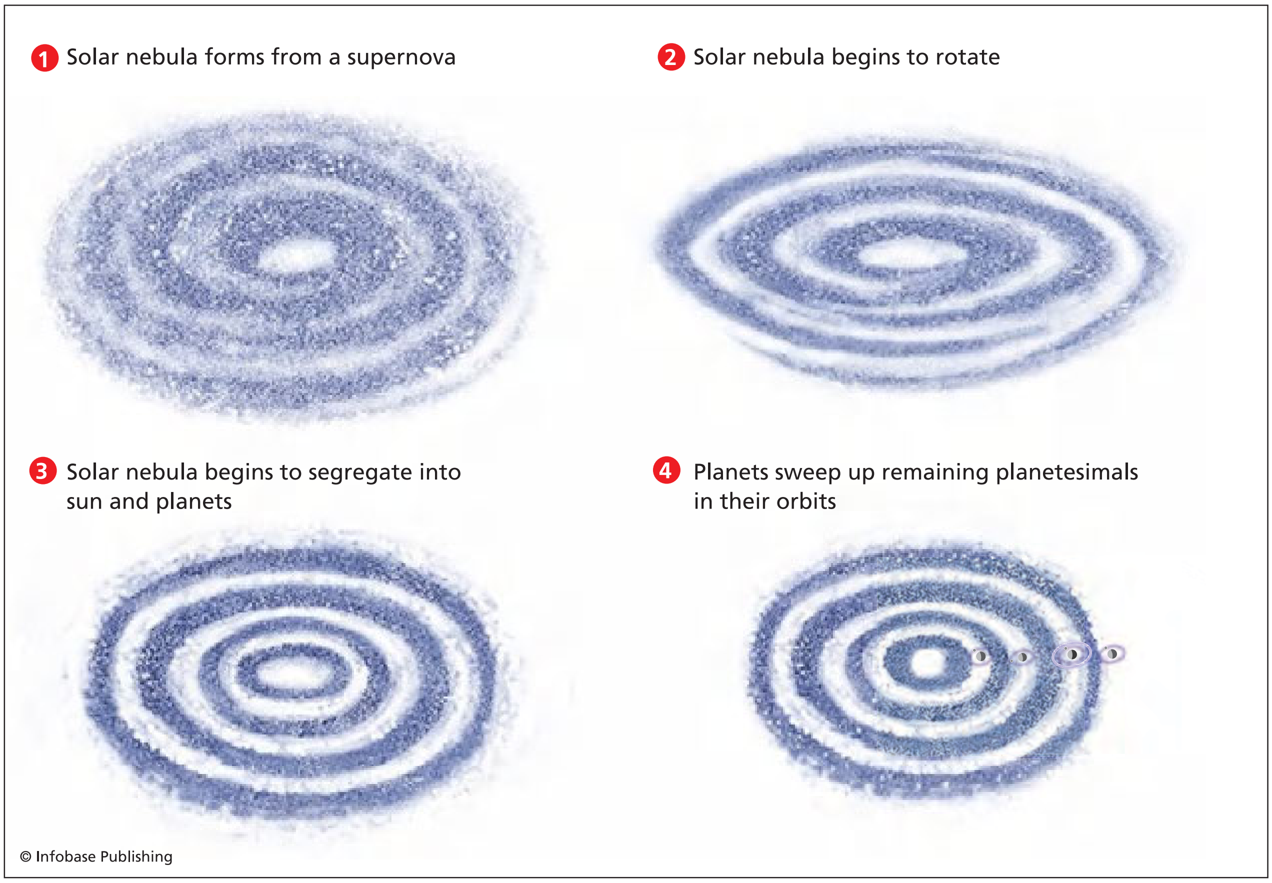
The condensation theory states that particles of interstellar dust (many of which formed in older supernovas) act as condensation nucleii that grow through accretion of other particles to form small planetesimals that then have a greater gravitational field that attracts and accretes other planetesimals and dust. Some collisions cause accretion, other collisions are hard and cause fragmentation and breaking up of the colliding bodies. The Jovian planets became so large that their gravitational fields were able to attract and accrete even free hydrogen and helium in the solar nebula.

This condensation theory explains the main differences between the planets due to distance from the Sun, since the temperature of the solar nebula would have decreased away from the center where the Sun formed. The temperature determines which materials condense out of the nebula, so the composition of the planets was determined by the temperature at their position of formation in the nebula. The inner terrestrial planets are made of rocky and metallic material because high temperatures near the center of the nebula allowed only the rocky and metallic material to condense from the nebula. Farther out, water and ammonia ices also condensed out of the nebula, because temperatures were cooler at greater distances from the early Sun.

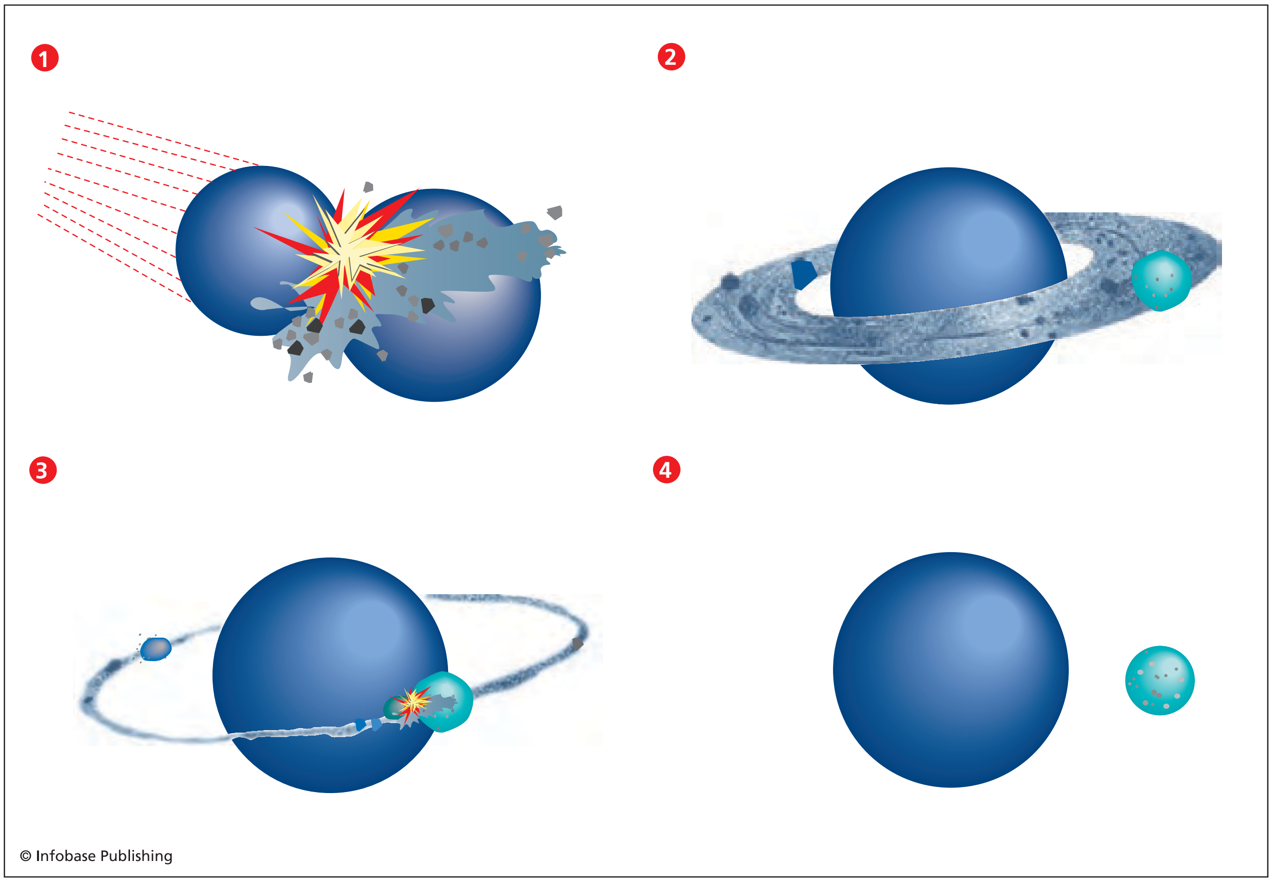
Early in the evolution of the solar system, the Sun was in a T-Tauri stage and possessed a strong solar wind that blew away most gases from the solar nebula, including the early atmospheres of the inner planets. Gravitational dynamics moved many of the early planetesimals into orbits in the Oort Cloud, where most comets and many meteorites are found. Some of these bodies have eccentric orbits that occasionally bring them into the inner solar system, and collisions with comets and smaller molecules likely brought the present atmospheres and oceans to Earth and the other terrestrial planets. Thus air and water, some of the basic building blocks of life, were added to the planet after it formed, being thrown in from deep space of the Oort Cloud.

The *Hadean* is the term used for the first of the four major eons of geological time: the Hadean, Archean, Proterozoic, and Phanerozoic. Some time classification schemes use an alternative division of early time, in which the Hadean is considered the earliest part of the Archean. As the earliest phase of Earth's evolution, ranging from accretion until approximately the age of first rocks [4.55 to 4.0 Ga (Ga = giga annee, or 10^9 years)], the Hadean is the most poorly understood interval of geologic time. Only a few mineral grains and rocks have been recognized from this Eon, so most of what is thought to be known about the Hadean is based on indirect geochemical evidence, meteorites, and models.

Between 4.55 and 3.8 Ga, meteorites bombarded the Earth; some were large enough to severely disrupt the surface, vaporize the atmosphere and ocean, and even melt parts of the mantle. By about 4.5 Ga, it appears as if a giant impactor, about the size of Mars, hit the protoearth. This impact ejected a huge amount of material into orbit around the protoearth, and some undoubtedly escaped. The impact probably also formed a new magma ocean, vaporized the early atmosphere and ocean (if present), and changed the angular momentum of the Earth as it spins and orbits



Formation of the solar system from condensation and collapse of a solar nebula



Sketch of the late great impact hypothesis for the origin of the Moon and melting of parts of the outer shell of the Earth early in its evolution

the Sun. The material in orbit coalesced to form the Moon, and the Earth-Moon system was born. Although not certain, this impact model for the origin of the Moon is the most widely accepted hypothesis, and it explains many divergent observations.

- The Moon's orbit is inclined by 5.1° from the ecliptic plane, whereas the Earth's orbit is inclined 23.4° from the ecliptic, suggesting that some force, such as a collision, disrupted the angular momentum and rotational parameters of the Earth-Moon system.
- The Moon is retreating from the Earth, resulting in a lengthening of the day by 15 seconds per year, but the Moon has not been closer to the Earth than 149,129 miles (240,000 km).
- The Moon is significantly less dense than the Earth and other terrestrial planets, being depleted in iron and enriched in aluminum, titanium, and other related elements.
- The oxygen isotopes of igneous rocks from the Moon are the same as from the Earth's mantle, suggesting a common origin.

These relationships suggest that the Moon did not form by accretion from the solar nebula at its present location in the solar system. The age of the Moon rocks shows that it formed at 4.5 Ga, with some magmatism continuing until 3.1 Ga, consistent with the impactor hypothesis.

The atmosphere and oceans of the Earth probably formed from early degassing of the interior by volcanism within the first 50 million years of Earth history. It is likely that the present atmosphere is secondary, in that the first or primary atmosphere would have been vaporized by the late great impact that formed the Moon, if it survived being blown away by an intense solar wind when the Sun was in a T-Tauri stage of evolution. The primary atmosphere would have been composed of gases left over from accretion, including primarily hydrogen, helium, methane, and ammonia, along with nitrogen, argon, and neon. The fact that the atmosphere has much less than the expected amount of these elements and is quite depleted in these volatile elements relative to the Sun suggests that the primary atmosphere has been lost to space.

Gases are presently escaping from the Earth during volcanic eruptions and also being released by weathering of surface rocks. Degassing of the mantle by volcanic eruptions, and perhaps also cometary impact, produced the secondary atmosphere. Gases released from volcanic eruptions include nitrogen (N), sulfur (S), carbon dioxide (CO_2), and water vapor (H_2O), closely matching the suite of volatiles that compose the present atmosphere and oceans. Most models show that little or no free oxygen was present in the early atmosphere, as oxygen was not produced until later, by photosynthetic life.

The early atmosphere was dense, with water vapor (H_2O), carbon dioxide (CO_2), sulfur (S), nitrogen (N), and hydrochloric acid (HCl). The mixture of gases in the early atmosphere would have caused greenhouse conditions similar to those presently existing on Venus. Since the early Sun during the Hadean era was approximately 25 percent less luminous than today, the atmospheric greenhouse served to keep temperatures close to their present range, where water is stable, and life can form and exist. As the Earth cooled, water vapor condensed to make rain that chemically weathered igneous crust, making sediments. Gases dissolved in the rain produced acids, including carbonic acid (H_2CO_3), nitric acid (HNO_3), sulfuric acid (H_2SO_4), and hydrochloric acid (HCl). These acids were neutralized by minerals (which are bases) that became sediments, and chemical cycling began. These waters plus dissolved components became the early hydrosphere, and chemical reactions gradually began changing the composition of the atmosphere, getting close to the dawn of life.

Speculation about the origin of life on Earth is of great intellectual interest. In the context of the Hadean, when life most likely arose, scientists are forced to consider different options for the initial trigger of life. Life could have come to Earth on late accreting planetesimals (comets) as complex organic compounds, or perhaps it came from interplanetary dust. If true, this would show how life got to Earth, but not how, when, where, or why it originated. Biological evidence supports the origination of life on Earth, in the deep sea near a hydrothermal vent or in shallow pools with the right chemical mixture. To start, life probably needed an energy source, such as lightning, or perhaps submarine hydrothermal vents, to convert simple organic compounds into building blocks of life—ribonucleic acids (RNA) and amino acids.

See also ARCHEAN; EARTH; LIFE'S ORIGINS AND EARLY EVOLUTION; METEOR, METEORITE; PLATE TECTONICS; SOLAR SYSTEM.

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origin and evolution of the universe

One of the deepest questions in cosmology, the science that deals with the study and origin of the universe and everything in it, relates to how the universe came into existence. Cosmologists estimate that the universe is 10–20 billion years old and consists of a huge number of stars grouped in galaxies, clusters of galaxies, and superclusters of galaxies, surrounded by vast distances of open space. The universe is thought to be expanding because measurements show that the most distant galaxies, quasars, and other objects in the universe are moving away from each other and from the center of the universe.

THE BIG BANG

The big bang is one of several theoretical beginning moments of the universe. The big bang theory states that the expanding universe originated 10–20 billion years ago in a single explosive event in which the entire universe suddenly exploded out of a single, minuscule, infinitely dense and hot particle, reaching a pea-sized supercondensed state with a temperature of 10 billion million million degrees Celsius in 1 million-million-million-million-million-millionth (10^{-36}) of a second after the big bang. Some of the fundamental contributions of the expanding universe models come from the German-born American physicist Albert Einstein, who in 1915 proposed the general theory of relativity, which described how matter and energy warp space-time to produce gravity. When Einstein applied his theory to the universe in 1917, he discovered that gravity would cause the universe to be unstable and collapse, so he proposed adding a cosmological constant as a "fudge factor" to his equations. The cosmological constant added a repulsive force to the general theory, and this force

Milky Way Galaxy. Astronomers and cosmologists must estimate the amount of matter, dark matter, and energy in the galaxies and the interstellar medium to test different models for the evolution of the universe *(Sander van Sinttruye, 2008, used under license from Shutterstock, Inc.)*

counterbalanced gravity, enabling the universe to continue expanding in his equations. Dutch mathematician, physicist, and astronomer William de Sitter (1872–1934) further applied Einstein's theory of general relativity to predict that the universe is expanding. In 1927 Belgian priest and astronomer Georges Lemaître (1894–1966) proposed that the universe originated in a giant explosion of a primeval atom, an event now called the big bang. In 1929 American astronomer Edwin Hubble (1889–1953) measured the movement of distant galaxies and discovered that galaxies are moving away from each other, expanding the universe as if the universe is being propelled from a big bang. This idea of expansion from an explosion negated the need for Einstein's cosmological constant, which he retracted, referring to it as his biggest blunder. This retraction, however, would later come back to haunt cosmologists.

Also in the 1920s, the Russian physicist and cosmologist from Odessa, George Gamow (1904–68), worked with a group of scientists and suggested that elements heavier than hydrogen, specifically helium and lithium, could be produced in thermonuclear reactions during the big bang. Later, in 1957, English astronomer Fred Hoyle (1915–2001) and his colleagues, American astrophysicist William Fowler (1911–55) and American physicists Geoff Burbidge (1925–) and British-born Margaret Burbidge (1919–), showed how hydrogen and helium could be processed in stars to produce heavier elements necessary to life, such as carbon, oxygen, and iron.

The inflationary theory is a modification of the big bang theory, and suggests that the universe underwent a period of rapid expansion immediately after the big bang. This theory, proposed in 1980 by American physicist Alan Guth (1947–), attempts to explain the present distribution of galaxies, as well as the 3 K cosmic background radiation discovered by American physicists and Nobel laureates Arno Penzias (1933–) and Robert Woodrow Wilson (1936–) in 1965. This uniformly distributed radiation is thought to be a relic left over from the initial explosion of the big bang. For many years after the discovery of the cosmic background radiation, astronomers searched for answers to the amount of mass in the universe and to determine how fast the universe was expanding and to what degree the gravitational attraction of bodies in the universe was

THE LARGE HADRON COLLIDER

Physicists go to extreme lengths to solve some of the deepest mysteries of the universe. The Large Hadron Collider (LHC) is a huge, 16.7-mile- (27-km-) long ring containing 9,300 superconducting magnets buried 109 yards (100 m) underground near Geneva, crossing the border between Switzerland and France. It is the world's largest particle accelerator (and the largest machine of any type in the world), designed to study the smallest known particles that are the building blocks of all things. The LHC has the potential to revolutionize the scientific understanding of subatomic particle physics and the large-scale structure of the universe. Each magnet must be cooled to 1.9 K (-456.3°F; -271.3°C) using liquid nitrogen and liquid helium before the accelerator is operated.

The collider works by taking two beams of particles, called hadrons, made either of proton or lead ions, and accelerates them toward each other in opposite directions around the collider in an ultrahigh vacuum. The particles can be made to travel around the hadron collider's loop many times to gain velocity, then they are aimed at each other so they collide. The two hadrons collide at extremely high energy, recreating conditions similar to those occurring just after the big bang. The experiments will be designed and the results monitored by scientific teams from around the world. When the particle accelerator is run at full power, trillions of protons will race around the track 11,245 times each second, travelling at 99.99 percent of the speed of light. Nearly 600 million collisions will take place every second, with energy of 14 Tev (teraelectronvolt). Temperatures generated at the collision points will be more than 100,000 times hotter than the center of the Sun, whereas the cooling rings surrounding the accelerator ring will be colder than outer space.

The particle detection system on the LHC contains the largest and most sophisticated detectors ever built, able to record the results of over 600 million proton collisions per second with micron (1-millionth of a meter) precision. The electronic trigger systems measure time for the passage of a particle to within a few billionths of a second, and the location of the particles is known to within a few millionths of a yard (m). These detectors feed the information to the most powerful scientific supercomputer in the world, including tens of thousands of computers located around the world in a distributed computing network called the Grid. The amount of data produced by experiments on the LHC will amount to about 1 percent of the world's information production rate, so a vast computer network is required to analyze and store the data.

The LHC ran into some problems that delayed its initial testing for many months, but it should shed new light on many unanswered questions in cosmology and the early history of the universe, as well as on fundamental particle physics. Some experiments are designed to determine why some particles have mass, while others apparently do not.

inhibiting the expansion. A relatively high density of matter in the universe would cause it to decelerate and eventually collapse back upon itself, forming a "big crunch," perhaps to be followed by a new big bang. Cosmologists called this the closed universe model. A low-density universe would expand forever, forming what cosmologists called an open universe. In between these end member models was a "flat" universe that would expand ever more slowly until it froze in place.

An alternative theory to the big bang is known as the steady state theory, in which the universe is thought to exist in a perpetual state with no beginning or end, with matter continuously being created and destroyed. The steady state theory does not adequately account for the cosmic background radiation. For many years cosmologists argued, almost religiously, whether the big bang theory or the steady state theory better explained the origin and fate of the universe. More recently, with the introduction of new high-powered instruments such as the Hubble space telescope, the Keck Mirror Array, and supercomputers, many cosmology theories have seen a convergence of opinion. A new, so-called standard model of the universe has been advanced and is currently being refined to reflect this convergence of opinion.

STANDARD MODEL OF THE UNIVERSE

In the standard model for the universe, the big bang occurred 14 billion years ago and marked the beginning of the universe. The cause and reasons for the big bang are not part of the theory, but left for the fields of religion and philosophy. Interestingly, ancient Jewish kabbalistic writings ranging from 700–1,500 years old concluded that the universe expanded from an object the size of a pea, roughly 15.34 billion years ago. Dr. William Percival of the University of Edinburgh leads a group of standard model cosmologists, and they calculate that the big bang occurred 13.89 billion years ago, plus or minus half a billion years. Most of the matter of

Data collected using the LHC may also shed light on why particles and atoms have the mass that they do. The LHC scientists plan to perform experiments designed to shed light on the distribution of mass in the universe—perhaps most importantly, that of dark matter. Contemporary models of cosmology suggest that the visible universe is only about 4 percent of the total matter in the universe, and the other 96 percent is made up of dark matter and dark energy, both extremely difficult to detect and study. When some dark matter is captured LHC scientists hope to be among the first to examine its properties, and consider the implications it has for the way the universe behaves.

Antimatter is similar to matter but has the opposite charge. A positron is similar to an electron but has a positive instead of a negative charge. Models for the early history of the universe suggest that at the big bang, equal amounts of matter and antimatter were created. When matter and antimatter meet they annihilate each other, releasing energy but losing matter. Scientists believe that most matter-antimatter pairs annihilated each other during early collisions, leaving only a small amount of matter in the entire universe, that forms all the matter visible (and invisible) today. Some experiments at the LHC will be geared to examine the differences between matter and antimatter and to try to understand why a small preference for one to be preserved led to such an imbalance in the universe.

The first second of the universe was the most dramatic second in the history of time. In this moment the universe expanded from essentially nothing, from a cocktail of fundamental particles about the size of a pea, into a rapidly expanding universe that would have the dimensions of time and space and the properties of mass and velocity. In the present universe ordinary matter consists of atoms, containing a nucleus made of protons and neutrons, in turn made of quarks that are bound together by gluons. Presently the bond between quarks and gluons is very strong, but in the first seconds of the early universe conditions would have been too hot and energetic for the gluons to hold the quarks together. The LHC will be able to reproduce the conditions in the first microseconds of the universe, so that scientists can investigate the physical environment of this hot, high-energy mixture of quarks and gluons, called a quark-gluon plasma.

There are complicated relationships between space and time. As the German-born American physicist Albert Einstein theorized, the three dimensions of space are related to time, and intense gravity fields can warp the space-time continuum. Further theoretical work has proposed that there may be even more hidden dimensions of space. String theory suggests that there may be numerous other dimensions to space, but they are difficult to observe. However, it is possible that these other dimensions may become detectable at the high energy conditions that will be created in the Large Hadron Collider.

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the universe is proposed to reside in huge invisible clouds of dark matter, thought to contain elementary particles left over from the big bang. Galaxies and stars reside in these huge clouds of matter and comprise a mere 4.8 percent of the matter in the universe. The dark matter forms 22.7 percent of the universe, leaving another 72.5 percent of the universe as nonmatter. At the time of the proposal of the standard model, this ambiguous dark matter had yet to be conclusively detected or identified. In 2002 the first-ever atoms of antimatter were captured and analyzed by scientific teams from CERN, the European Laboratory for Particle Physics. In October of 2008 CERN opened a new generation of instruments designed to test theories of particle physics, the Large Hadron Collider, which is the largest particle accelerator (and largest scientific instrument) in the world. Unfortunately, the instrument suffered some serious malfunctions on its initial opening, and experiments were not carried out until 2009.

Detailed observations of the cosmic background radiation by space-borne platforms such as NASA's *Cosmic Background Explorer (COBE)* that in 1992 revealed faint variations and structure in the background radiation, are consistent with an inflationary, expanding universe. Blotches and patterns in the background radiation reveal areas that may have been the seeds or spawning grounds for the origin of galaxies and clusters. Detailed measurements of this background radiation have revealed that the universe is best thought of as flat—however, the lack of sufficient observable matter to have a flat universe requires the existence of some invisible dark matter. These observations were further expanded in 2002 and 2004, when teams working with the Degree Angular Scale Interferometer (DASI) experiment reported directional differences (called polarizations) in the cosmic microwave background radiation dating from 450,000 years after the big bang. The astronomers were able to relate these directional differences to forces that led to the formation of galaxies and the overall structure of the universe today. These density differences are quantum effects that effectively seeded the early universe with protogalaxies during the early inflation period, and their observation provides strong support for the standard model for the universe.

Recent measurements have shown that the rate of expansion of the universe seems to be increasing, which has led cosmologists to propose the presence of a dark energy that is presently largely unknown. This dark energy is thought to comprise the remaining 72.5 percent of the universe, and it is analogous to a repulsive force or antimatter. Recognition in 1998 that the universe is expanding at ever-increasing rates has toppled questions about open versus closed universe models and has drastically changed perceptions of the fate of the universe. Amazingly, the rate of acceleration of expansion is remarkably consistent with Einstein's abandoned cosmological constant. The expansion seems to be accelerating so rapidly that eventually the galaxies will be moving apart so fast that they will not be able to see each other and the universe will become dark. Other cosmologists argue that so little is known of dark matter and dark energy that it is difficult to predict how it will act in the future, and the fate of the universe is not determinable from present observations and knowledge.

Alan Guth and coworkers recently proposed modifications of the inflationary universe model. They suggested that the initial inflation of the universe, in its first few microseconds, can happen over and over again, forming an endless chain of universes, called multiverses by Dr. Martin Rees of Cambridge University. With these ideas, our 14 billion-year-old universe may be just one of many, with big bangs causing inflations of the perhaps infinite other universes. According to the theories of particle physics, it takes only about one ounce of primordial starting material to inflate to a universe like our own. The process of growing chains of bubble-like universes through multiple big bangs and inflationary events has been termed eternal inflation by Dr. Andrei Linde of Stanford University.

Cosmologists, astronomers, and physicists are searching for a grand unifying theory that is able to link Einstein's general relativity with quantum mechanics and new observations of our universe. One attempt at a grand unifying theory is the string theory, in which elementary particles are thought to be analogous to notes being played on strings vibrating in 10- or 11-dimensional space. A newer theory emerging is called M-theory (for membrane theory or matrix theory), in which various dimensional membranes including universes can interact and collide, setting off big bangs and expansions that could continue or alternate indefinitely.

Cosmology and the fate of theories like the big bang are undergoing rapid and fundamental changes in understanding, induced by new technologies, computing abilities, and philosophy and from the asking of new questions about creation of the universe. Although it is tempting to think of current theories as complete, perhaps with a few unanswered questions, history tells us that much can change with a few new observations, questions, or understanding.

See also ASTRONOMY; ASTROPHYSICS; BINARY STAR SYSTEMS; BLACK HOLES; COSMIC MICROWAVE BACKGROUND RADIATION; COSMOLOGY; GALAXIES; GALAXY CLUSTERS; PULSAR; QUASAR; RADIO GALAXIES; SUPERNOVA.

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ScienceDaily: Astrophysics News. ScienceDaily LLC. Available online. URL: http://www.sciencedaily.com/news/space_time/astrophysics/. Accessed October 24, 2008.

orogeny The process of building mountains is known as orogeny. For several or tens of centuries, many early philosophers, theologians, and scientists going back at least as far as Francis Bacon (1561–1626) were formulating theories about the forces involved in uplifting and deforming mountains. By the middle 1800s, the processes involved in the formation of mountains became known as orogeny. Early ideas suggested that mountains were deformed and uplifted by magmatic intrusions, or reflected an overall contraction of the Earth with mountain belts representing cooling wrinkles as on a shriveled prune. In a classical work in 1875, Eduard Suess published *Die Entstehung der Alpen* (The origin of mountains) in which he argued that the pattern of mountain belts on the planet did not follow any regular pattern that would indicate global contraction, and he suggested that the mountain belts represented contraction between rigid blocks (now called cratons) and surrounding rocks on the margins of these massifs. However, he still believed that the main driving force was global contraction induced by cooling of the Earth. In Suess's last volume of *Das Antlitz* *der Erde* (The Face of the Earth, 1909), he admitted that the amount of shortening observed in mountain belts was greater than global cooling and contraction could explain, and he suggested that perhaps other translations, or movements of crustal blocks, have occurred in response to tidal forces and the rotation of the planet.

In 1915 and 1929 Alfred Wegener published *Die Entstehung der Kontinente* and *Die Entstehung der Kontinente und Ozeane* (The origin of the continents and the oceans). Wegener argued strongly for large horizontal motions between cratons made of sial (light continental crust), and using such data as the match of restored coastlines and paleontological data, he founded the theory of continental drift. Several geologists, including Alex du Toit, Reginald Daly, and Arthur Holmes documented geological ties between different continents supporting the idea of continental drift. In the 1940s–60s, geophysical exploration of the seafloor led to the recognition of seafloor spreading, and provided the data that J. Tuzo Wilson needed to propose the modern theory of plate tectonics in 1965.

With the development of the ideas of plate tectonics, geologists now recognize that mountain belts are of three basic types: fold-and-thrust belts, volcanic mountain ranges, and fault block ranges. Fold-and-thrust belts are contractional mountain belts, formed where two tectonic plates collided, forming great thrust faults, folds, metamorphic rocks, and volcanic rocks. Detailed mapping of the structure in the belt enables geologists to reconstruct their history, and essentially pull them back apart. Many of the rocks in fold-and-thrust belt types of mountain ranges were deposited on the bottom of the ocean, or continental rises, slopes, or shelves, or on ocean margin deltas. When the two plates collide, many of the sediments get scraped off and deformed, forming the mountain belts; thus, these belts mark places where oceans have closed. Volcanic mountain ranges include places such as Japan's Fuji and Mount St. Helens in the Cascades of the western United States. Volcanism associated with subduction and plate tectonics, rather than deformation, primarily forms these mountain ranges. Fault-block mountains, such as the Basin and Range Province of the western United States, are formed by the extension or pulling apart of the continental crust, forming elongate valleys separated by tilted fault-bounded mountain ranges.

See also CONTINENTAL DRIFT: CONVERGENT PLATE MARGIN PROCESSES; DIVERGENT PLATE MARGIN PROCESSES; PLATE TECTONICS.

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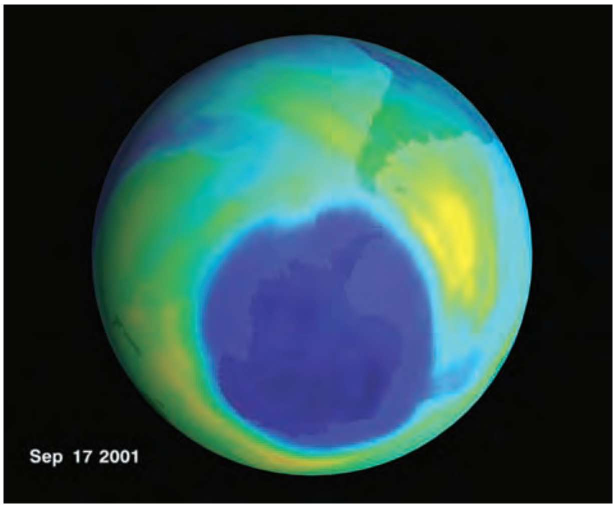
ozone hole Ozone (O_3) is a poisonous gas that is present in trace amounts in much of the atmosphere, but reaches a maximum concentration in a stratospheric layer between 9 and 25 miles (15–40 km) above the Earth, with a peak at 15.5 miles (25 km). The presence of ozone in the stratosphere is essential for most life on Earth, since it absorbs the most carcinogenic part of the solar spectrum with wavelengths between 0.000011 and 0.0000124 inches (280 and 315 nm). If these ultraviolet rays reached the Earth they would cause many skin cancers, and possibly depress the human immune system. These harmful rays would greatly reduce photosynthesis in plants and reduce plant growth to such an extent that the global ecosystems would crash.

Ozone naturally changes its concentration in the stratosphere, and is also strongly affected by human or anthropogenically produced chemicals that make their way into the atmosphere and stratosphere. Ozone is produced by photochemical reactions above 15 miles (25 km), mostly near the equator, and moves toward the poles, where it is most abundant and where it is gradually destroyed. The concentration of ozone does not vary greatly in equatorial regions, but at the poles tends to be the greatest in the winter and early spring. The formation of a strong vortex that isolates the stratospheric air over the pole characterizes stratospheric circulation during the night in the Antarctic winter.

Atmospheric and stratospheric flow dynamics can change the distribution of ozone, solar flare and sunspot activity can enhance ozone, and volcanic eruptions can add sulfates to the stratosphere that destroy ozone. In the 1970s scientists realized that some aerosol chemicals and refrigerants, such as chlorofluorocarbons (CFCs), could make their way into the stratosphere, where ultraviolet light broke them down, releasing ozone-destroying chlorine.



Satellite data shows the Antarctic ozone hole, 9/17/01. The hole is roughly the size of North America *(NASA Goddard Space Flight Center [NASA-GSFC])*

Environmental regulations subsequently curtailed the use of CFCs, but the aerosols and chlorine have long residence times in the stratosphere, and each chlorine ion is capable of destroying large amounts of ozone. Since the middle 1980s, a large hole marked by large depletions of ozone in the stratosphere has been observed above Antarctica every spring, its growth aided by the polar vortex. The hole has continued to grow, but the relative contributions to the destruction of ozone by CFCs, other chemicals (such as supersonic jet and space shuttle fuel), volcanic gases, and natural fluctuations is uncertain. In 1999 the size of the Antarctic ozone hole was measured at more than 9,650,000 square miles (25 million km^2), more than two and half times the size of Europe. The appearance of ozone depletion above Arctic regions has added credence to models that show the ozone depletion being largely caused by CFCs. Many models suggest that the CFCs may lead to a 5–20 percent reduction in global ozone, with consequent increases in cancers and disease and loss of crop and plant yield.

See also ATMOSPHERE; CLIMATE CHANGE; ELECTROMAGNETIC SPECTRUM; GLOBAL WARMING; METEOROLOGY.

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paleoclimatology Paleoclimatology is the study of past and ancient climates, their distribution and variation in space and time, and the mechanisms of long-term climate variations. A wide variety of different types of data are used to determine past climates, such as the distribution of certain plant and animal species that are climate sensitive and the distribution of certain rock types that form in restricted climate conditions. Other types of data serve as paleoclimate indicators, including tree-ring studies (dendrochronology), ice-core data, cave deposits (speleothems), and lake sediment studies. Increasingly, studies are using isotopic data, such as ratios between light and heavy oxygen isotopes, as paleoclimate indicators since these ratios are very sensitive to past global climates, glaciations, and elevations at which rainwater fell.

Most paleoclimate studies reveal that there have been major climate shifts on the planet throughout Earth history, with periods of near global glaciation, periods of intense heat and humidity, or hot and dry weather, and more temperate periods such as the current interglacial stage. Many factors play a role in climate change, including orbital and astronomical variations described by Milankovitch cycles, plate tectonics and the distribution of continental land masses, and volcanic productivity.

Paleoclimate studies have been used widely by scientists who study the past distribution of continents in supercontinents and continental drift. For instance, if a continental land mass moves equatorial regions to more polar regions, it will experience a progressive shift in the surface climates. Any rocks deposited during these different climates will reflect the climatic conditions that prevailed during that time period, and any plant or animal fossils in the rocks will reflect species that were able to survive under the prevailing climate conditions. Thus, studying the rock record reveals information not only about the past climates for a continental block, but also the history of climate zones that a plate or continental block moved through during its drift across the surface of the Earth.

See also CLIMATE; CLIMATE CHANGE; MILANKOVITCH CYCLES; PLATE TECTONICS; SUPERCONTINENT CYCLES.

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Paleolithic The Paleolithic is the first division of the Stone Age in archaeological time, marked by the first appearance of humans and their associated tools and workings. The time of the Paleolithic corresponds generally with the Pleistocene (from 1.8 million years ago until 10,000 years ago) of the geological time scale, Earth's most recent period of repeated glaciations, but varies somewhat from place to place. The Paleolithic began with the first use of stone tools about 2.5 or 2.6 million years ago and ended with the introduction of agriculture at the end of the Pleistocene about 10,000 years ago. Artifacts that have survived from the Paleolithic are known as paleoliths.

Human technological prehistory is divided into three periods; the Stone Age, the Bronze Age, and the

Iron Age. Modern divisions of the Stone Age stretch from the Paleolithic to Neolithic according to the following scheme:

- Pleistocene epoch, a time of heavy glaciation
- Holocene epoch, a time of modern climate, divided into the Mesolithic, Epipaleolithic, and Neolithic ages, Copper Age, Bronze Age, and Iron Age, and
- the Historical period, from when modern records began.

During the Paleolithic a race of ancient hominids known as Neanderthals (also spelled Neandertals) inhabited much of Central Asia, the Middle East, Near East, western Siberia, and Europe, especially throughout the past 200,000 years during the Pleistocene ice ages. Neanderthals were heavily built and had large brains, and were probably adapted to the cold climate conditions in the periglacial environments they inhabited (i.e., they were probably hairy and fatty). These premodern humans were few in number, dwindled in numbers around 40,000 years ago, and disappeared into extinction by around 27,000 years ago.

The first remains of modern humans (*Homo sapiens sapiens*) are dated at around 30,000 to 40,000 years old and show that modern humans inhabited some of the same areas as the Neanderthals. The overlapping time and space ranges of Neanderthals and modern humans raises questions about the origins of modern humans and relationships between the two groups of hominids. Archaeologists debate whether the Neanderthals went extinct because they were hunted and killed by the modern humans, or whether perhaps climate conditions became unbearable to the Neanderthals and they simply died off. There is very little evidence about whether modern humans and Neanderthals lived in peace side by side, possibly interbreeding, or if they fought or avoided each other. Some questions relate to whether or not modern humans evolved from Neanderthals, if the two races of hominids are unrelated, or if they share common distant ancestors. A possible transitional form between Neanderthals and *Homo sapiens sapiens* has been described from Mount Carmel in Israel, although most genetic evidence so far suggests that the modern humans did not evolve from Neanderthals. Modern humans seem to have descended from a single African female that lived 200,000 years ago, although some theories suggest that humans evolved in different parts of the world at virtually the same time.

Understanding of the evolution of humans is a controversial and constantly changing field. Genetic studies show that humans and chimpanzees had a common ancestor that lived about 5–10 million years ago. The earliest known human ancestor is australopithecine, from 3.9–4.4-million-year-old hominids found in Ethiopia and Kenya. It is thought that australopithecine evolved into *Homo habilis* by 2 million years ago. *Homo habilis* was larger than australopithecine, walked upright, and was the first hominid to use stone tools. By 1.7 million years ago, *Homo erectus* appeared in Africa, probably evolving from *Homo habilis*. *Homo erectus* had prominent brow ridges, a flattened cranium and a rounded jawbone and was the first hominid to use fire and migrate out of Africa as far as China, Europe, and the British Isles. Modern humans (*Homo sapiens sapiens*) and Neanderthals (*Homo sapiens neanderthalensis*) are both probably descendants from *Homo erectus*.

Neanderthals were hunters and gatherers who roamed the plains, forests, and mountains of Europe and Eurasia. They left many stone tools, clothing, and possibly some art including cave drawings and sculptures. Around 40,000–30,000 years ago, the Neanderthals found their environments increasingly inhabited by modern humans, who had smaller, less robust skeletons and smaller brains and lacked many of the primitive traits that characterized earlier humans. Some early modern humans had some Neanderthal traits, but there is considerable debate in the anthropological community about whether this indicates an evolutionary trend, or more likely, that the two races interbred, producing mixed offspring. Whether the interbreeding was peaceful or a consequence of war and raids, there is no evidence that the mixed offspring successfully developed into a separate mixed race. The genetic and most archaeological evidence suggests that modern humans evolved separately, from a single African female, whose descendants came out of Africa and inhabited the Near East, Europe, and Asia.

These debates in the scientific community highlight two competing hypotheses for the origin of modern humans. The out-of-Africa theory follows the genetic evidence that modern humans arose about 200,000 years ago in Africa and spread outward, replacing older indigenous populations of Neanderthals and other hominids by 27,000 years ago. An opposing theory, called the multiregional evolution theory, argues that all modern humans are not descended from a single 200,000-year-old African ancestor. This model supposes that modern humans have older ancestors, such as *Homo erectus,* that spread out to Europe and Asia by 1 or 2 million years ago, then evolved into separate races of *Homo sapiens sapiens* independently in different parts of the world. There are many arguments against this theory of multiregional parallel evolution, the strongest of which notes the unlikelihood of the same evolutionary path being followed independently in several different places at the same time. However, the multiregionalists argue that the evolutionary advances were driven by similar technological and lifestyle advances and that many adjacent groups may have been interbreeding and thereby exchanging genetic material. The multiregionalists need to allow enough genetic exchange between regional groups to form an early worldwide-web dating or genetic exchange system, whereby enough traits are transmitted between groups to keep *Homo sapiens sapiens* the same species globally, but to keep enough isolation so that individual groups maintain certain distinctive traits.

The multiregionalists see a common ancient ancestor 1–2 million years ago, with different groups evolving to different degrees toward what we call modern humans. In contrast, the out-of-Africans see different branches from *Homo erectus* 200,000 years ago, with Neanderthals first moving into Eurasia and the Middle East, to be later replaced by migrating early modern humans that followed the migrating climate zones north with the retreat of the Pleistocene glaciers.

See also EVOLUTION; ICE AGES; NEOLITHIC; PLEISTOCENE.

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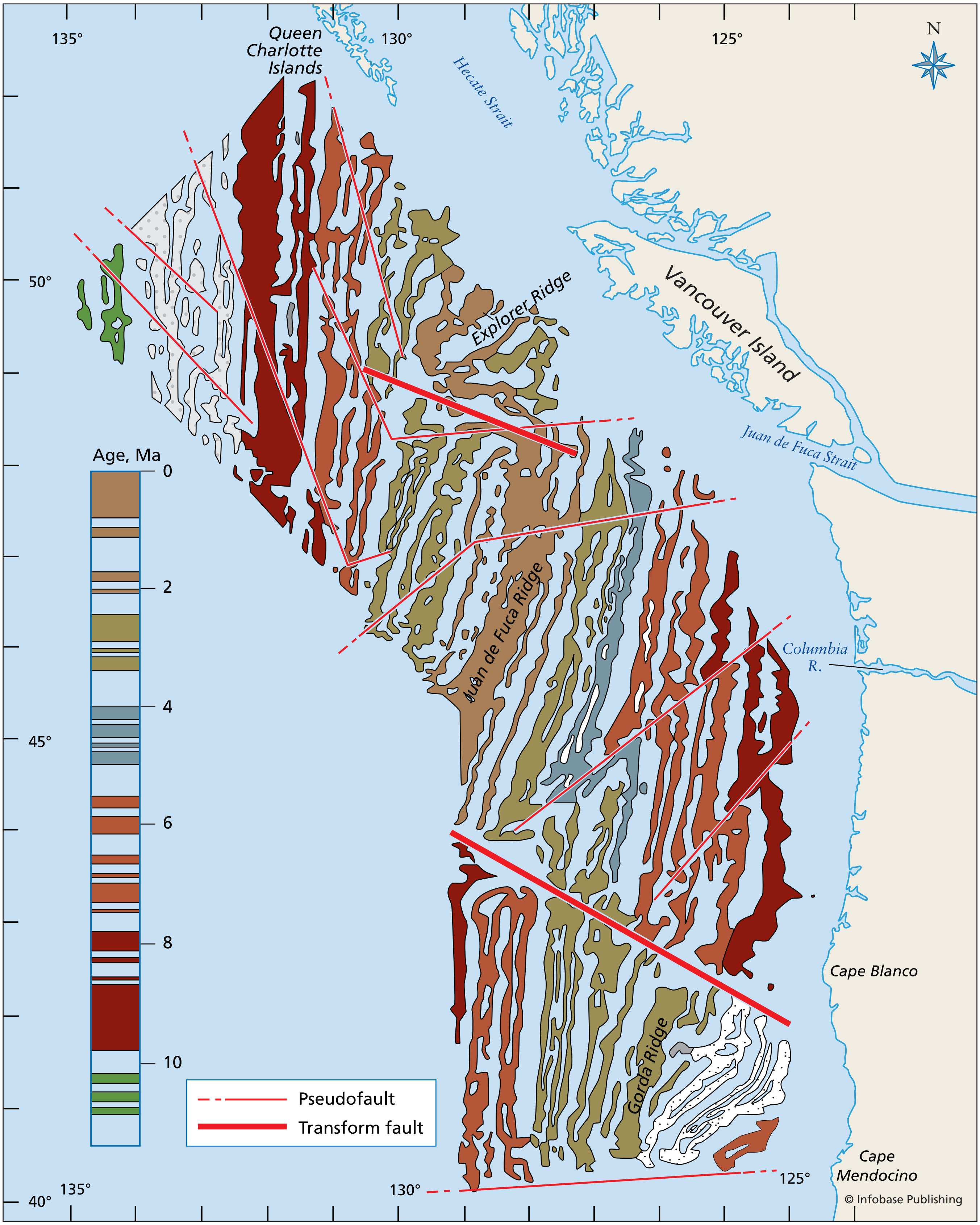
paleomagnetism Paleomagnetism is the study of natural remnant magnetism in rocks with the goal of understanding the intensity and direction of the Earth's magnetic field in the geologic past and understanding the history of plate motion. The Earth's magnetic field can be divided into two components at any location—the declination and the inclination. The declination measures the angular difference between the Earth's rotational north pole and the magnetic north pole. The inclination measures the angle at which the magnetic field lines plunge into the Earth. The inclination is 90° at the magnetic poles and 0° halfway between the poles.

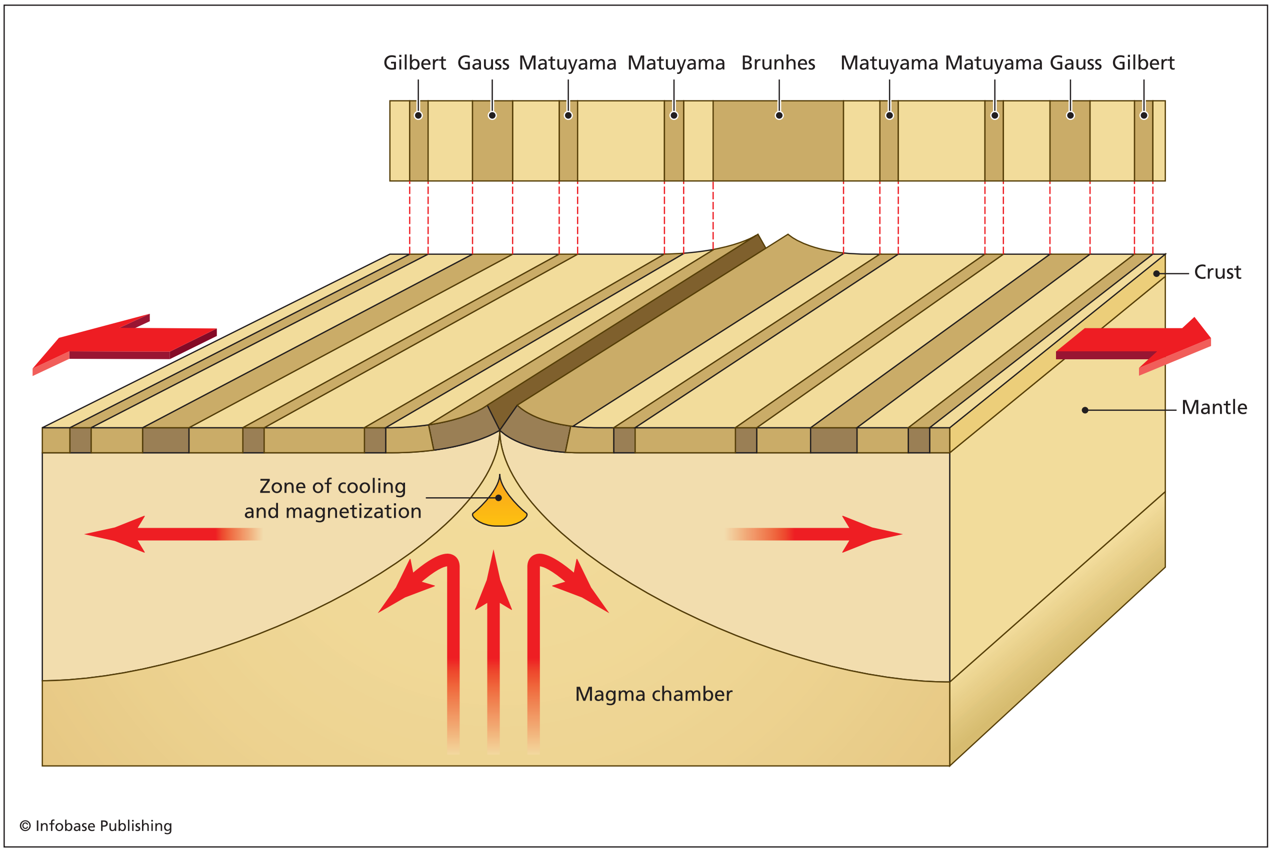
Studies of paleomagnetism in young rocks have revealed that the Earth's magnetic poles can flip suddenly, over a period of thousands or even hundreds of years. The magnetic poles also wander by about 10–20° around the rotational poles. On average, however, the magnetic poles coincide with the Earth's rotational poles. A researcher can use this coincidence to estimate the north-south directionality in ancient rocks that have drifted or rotated in response to plate tectonics. Determination of the natural remnant magnetism in rock samples can, under special circumstances, reveal the paleo-inclination and paleo-declination, which can be used to estimate the direction and distance to the pole at the time the rock acquired the magnetism. If these parameters can be determined for a number of rocks of different ages on a tectonic plate, then an apparent polar wander path for that plate can be constructed. These show how the magnetic pole has apparently wandered with respect to (artificially) holding the plate fixed—when the reference frame is switched, and the pole is held fixed, the apparent polar wander curve shows how the plate has drifted on the spherical Earth.

Paleomagnetism played an enormous role in the confirmation of seafloor spreading, through the discovery and understanding of seafloor magnetic anomalies. In the 1960s geophysicists surveyed the magnetic properties of the ocean floor and began to discover some amazing properties. The seafloor has a system of linear magnetic anomalies where one "stripe" has its magnetic minerals all oriented the same way as the present magnetic field, and the magnetic minerals in alternate stripes are oriented in the opposite direction. These stripes are oriented parallel to the mid-ocean ridge system; where transform faults offset the ridges, the anomalies are also offset. The anomalies are symmetric on either side of the ridge, and the same symmetry is found across ridges worldwide.

Understanding the origin of seafloor magnetic stripes was paramount in acceptance of the plate tectonic paradigm. The magnetic stripes form in the following way. As oceanic crust is continuously formed at mid-ocean ridges, as if it were being extruded from a conveyor belt, all the magnetic minerals tend to align with the present magnetic field when the new crust forms. The oceanic crust thus contains a record of when and for how long the Earth's magnetic field has been in the "normal" position, and when and for how long it has been "reversed." Terrestrial rock sequences exhibit similar reversals of the Earth's magnetic field, and many of these have been dated. Using these data, geologists have established a magnetic polarity reversal time scale. The last reversal was about 700,000 years ago, and the one before that, about 2.2 million years ago. Oceanic crust is as old as Jurassic, and documentation of the age of seafloor magnetic stripes has led to the construction



Seafloor magnetic stripes in the northeast Pacific Ocean produced by seafloor spreading on the Juan de Fuca, Gorda, and Explorer ridges



Symmetric magnetic anomalies produced by conveyor-belt style production of oceanic crust in an alternating magnetic field. The magnetic polarity timescale, above, is constructed by dating rocks with different magnetizations.

of the magnetic polarity time scale back to 170 million years ago.

See also MAGNETIC FIELD, MAGNETOSPHERE; PLATE TECTONICS.

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paleontology Paleontology is the study of past life based on fossil evidence, with a focus on the lines of descent of organisms and the relationships between life and other geological phenomena. Information from fossil distributions is used to understand ancient environments and climates and to determine the boundaries of former ties between landmasses that are now separated. Many paleontologists are also concerned with mechanisms of extinction and the appearance of new organisms, as well as the mode of life of organisms and their evolution. In the past, paleontology was mostly a descriptive science describing the morphology of fossils, but in recent years it has become much closer to biology, with a new science of geobiology emerging. In this approach, many biological methods are applied to the study of fossils, including cladistic methods, functional morphology, and even paleogenetic studies.

The preservation of the remains of organisms as fossils is a rare event and therefore represents unusual conditions, not necessarily representative of life at the time the organism lived. Despite this limitation, fossils are the best way to understand the past history of life on Earth. To correctly interpret the fossil record paleontologists must use statistical techniques to try to interpret the bias in the record and to understand the variations in the environment that may have led to some organisms being preserved while others were destroyed.

Organisms may leave traces of their former existence in body fossils, in which the body of the organism itself is preserved or replaced with other elements and preserved in shape, or as trace fossils, in which footprints, burrows, or other vestiges of the organism's having influenced the environment are left behind in the geological record. An organism may also leave evidence of its influence through geochemical tracers that can yield clues about the life-forms and how they interacted with their environment.

The science of paleontology experienced major changes in the 1970s and 1980s. In past centuries paleontology was mostly concerned with the taxonomy and anatomy of fossils, with tremendous efforts spent on describing and classifying small details of fossil morphology. The revolution in paleontology resulted from the mixture of taxonomy with biology, to form a new field of paleobiology in which the paleontologists asked new questions, such as how much of a preservational bias is there in the geological record, and what does the fossil record reveal about evolution. Some paleontologists began investigating the causes of mass extinctions, whereas others study the interactions of plate tectonics and the development and evolution of life in the field of paleobiogeography.

MAIN LIFE GROUPS

Metazoa are complex multicellular animals in which the cells are arranged in two layers in the embryonic gastrula stage. The Metazoa are extremely diverse and include 29 phyla, most of which are invertebrates. The phylum Chordata is an exception.

The Metazoa appeared about 620 million years ago and experienced a rapid explosion around the Precambrian-Cambrian boundary, probably associated with the formation and breakup of the supercontinents Rodinia and Gondwana and the rapidly changing environments associated with the supercontinent cycle. They evolved from eukaryotes, single-celled organisms with a nucleus, that appeared around 1,600 million years ago. Prokaryotes are older, probably extending back past 3,800 million years ago.

Some of the oldest soft-bodied Metazoa are remarkably well preserved in the Ediacarian fauna from southeast Australia and other locations around the world. These fauna include a remarkable group of very unusual shallow marine forms, including some giants up to a meter in length. This explosion from simple, small single-celled organisms that existed on Earth for the previous three billion years (or more) is truly remarkable. The Ediacarian fauna (and related fauna, collectively called the Vendoza fauna) died off after the period between 620–550 million years ago, as these organisms show no affinity with modern invertebrates.

After the Ediacarian and Vendoza fauna died off, other marine invertebrates saw a remarkable explosion through the Cambrian. These organisms in the Cambrian included shelly fossils, trilobites, brachiopods, mollusks, archeocyathids, and echinoderms, and eventually in the Ordovician were joined by crinoids and bryozoans. Modern Metazoa include a variety of organisms including corals, gastropods, bivalves, and echinoids.

See also CLOUD, PRESTON; EVOLUTION; FOSSIL; GRABAU, AMADEUS WILLIAM; HISTORICAL GEOLOGY; LIFE'S ORIGINS AND EARLY EVOLUTION; PHANEROZOIC.

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Paleozoic

The era of geologic time that includes the interval between 544 and 250 million years ago and the erathem of rocks deposited in this interval, called the Paleozoic, includes seven geological periods and systems of rocks: the Cambrian, Ordovician, Silurian, Devonian, Carboniferous (Mississippian and Pennsylvanian), and Permian. The name *Paleozoic,* meaning ancient life, was coined by British geologist Adam Sedgwick in 1838 for the deformed rocks underlying the Old Red Sandstone in Wales. The base of the Paleozoic is defined as the base of the Cambrian period, conventionally taken as the lowest occurrence of trilobites. Recently however, with the recognition of the advanced Vendian and Ediacaran fauna, the base of the Cambrian was reexamined and has been defined using fossiliferous sections in eastern Newfoundland and Siberia to be the base of an ash bed dated at 544 million years ago.

At the beginning of the Paleozoic, the recently formed supercontinent of Gondwana was breaking apart, but later regrouped as Pangaea by the Carboniferous. This supercontinent included the southern continents in the Gondwanan landmass and the northern continents in Laurasia, separated by the Pleionic and Tethys Oceans, and surrounded by the Panthalassa Ocean. With the breakup of the late Precambrian supercontinent, climates changed from icehouse to hothouse conditions. The volume of carbon dioxide (CO_2) emitted to the atmosphere by the mid-ocean ridge system caused this dramatic change. During supercontinent periods, the length of the ridge system is small, and relatively small amounts of CO_2 are emitted to the atmosphere. During supercontinent breakup however, much more CO_2 is released during enhanced volcanism associated with the formation of new ridge systems. Since CO_2 is a greenhouse gas, supercontinent breakup is associated with increasing temperatures and the establishment of hothouse conditions. The Pangaean supercontinent then experienced continental climates ranging from hot and dry to icehouse conditions, with huge continental ice sheets covering large parts of the southern continents. Many collisional and rifting events occurred, especially along the active margins of Pangaea, necessitating the subduction of huge tracts of oceanic crust in order to accommodate these collisional events.

The dramatic changes in continental configurations, the arrangement of ecological niches, and the huge climatic fluctuations at the base of the Paleozoic are associated with the most dramatic explosion of life in the history of the planet. Hard-shelled organisms first appeared in the lower Cambrian and are abundant in the fossil record by the mid-Cambrian. Fish first appeared in the Ordovician. All of the modern animal phyla and most of the plant kingdom are represented in the Paleozoic record, with fauna and flora inhabiting land, shallow seas, and deep-sea environments. There are several mass extinction events in the Paleozoic in which large numbers of species suddenly died off and were replaced by new species in similar ecological niches.

In addition to the development of hard-shelled organisms and skeletons, the Paleozoic saw the dramatic habitation of the terrestrial environment. Bacteria and algae crept into different environments such as soils before the Paleozoic, with land plants appearing in the Silurian. Dense terrestrial flora expanded by the Devonian and culminated in the dense forests of the Carboniferous. This profoundly changed the weathering, erosion, and sedimentation patterns from that of the Precambrian, and also significantly affected the atmosphere-ocean composition. Terrestrial fauna rapidly followed the plants onto land, with tetrapods roaming the continents by the Middle or Late Devonian. By the Devonian, invertebrates including spiders, scorpions, and cockroaches had invaded the land, and fish became abundant in the oceans.

In the Carboniferous much organic carbon got buried, reducing atmospheric CO_2 levels and ending the hothouse conditions. With the formation of Pangaea in the Carboniferous and Permian, global ridge lengths were reduced, and less CO_2 was released to the atmosphere. Together with the burial of organic carbon, new icehouse conditions were established, stressing the global fauna and flora. The largest mass extinction in geological history marks the end of the Paleozoic (end-Permian mass extinction) and the start of the Mesozoic. The causes of this dramatic event seem to be multifold. Conditions on the planet included the formation of a supercontinent (Pangaea), falling sea levels, evaporite formation, and rapidly fluctuating climatic conditions. At the boundary between the Paleozoic and Mesozoic Periods (245 million years ago), 96 percent of all species became extinct, including marine organisms such as the rugose corals, trilobites, many types of brachiopods, and many foraminifera species.

The Siberian flood basalts were erupted over a period of less than 1 million years 250 million years ago, at the end of the Permian at the Permian-Triassic boundary. They are remarkably coincident in time with the major Permian-Triassic extinction, implying a causal link. They cover a large area of the Central Siberian Plateau northwest of Lake Baikal and are more than half a mile thick over an area of 210,000 square miles (544,000 km^2), but they have been significantly eroded from an estimated volume of 1,240,000 cubic miles (5,168,500 km^3). The rapid volcanism and degassing could have released enough sulfur dioxide to cause a rapid global cooling, inducing a short ice age with an associated rapid fall of sea level. Soon after the ice age took hold the effects of the carbon dioxide took over and the atmosphere heated, resulting in a global warming. The rapidly fluctuating climate postulated to have been caused by the volcanic gases is thought to have killed off many organisms, which were simply unable to cope with the wildly fluctuating climate extremes.

Another possibility is that the impact of a meteorite or asteroid with the Earth aided the end-Permian extinction, adding environmental stresses to an already extremely stressed ecosystem. If additional research proves this to be correct, it will be shown that a one-two-three punch, including changes in plate configurations and environmental niches, dramatic climate changes, and extraterrestrial impacts together caused history's greatest calamity.

See also CAMBRIAN; CARBONIFEROUS; DEVONIAN; EVOLUTION; FOSSIL: GONDWANA, GONDWANALAND; PANGAEA; PERMIAN; SILURIAN.

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Pangaea Pangaea was the supercontinent that formed in the Late Paleozoic, lasting from about 300–200 million years ago, and included most of the planet's continental masses. The former existence of Pangaea, meaning all land, was first postulated by Alfred Wegener in 1924, when he added the Australian and Antarctic landmasses to an 1885 supercontinent reconstruction of Gondwana by Eduard Suess that included Africa, India, Madagascar, and South America. He used the fit of the shapes of the coastlines of the now dispersed continental fragments, together with features such as mineral belts, faunal and floral belts, mountain ranges, and paleoclimate zones that matched across his reconstructed Pangaean landmass to support the hypothesis that the continents were formerly together. Wegener proposed that the supercontinent first broke up into two large fragments including Laurasia in the north and Gondwana in the south, and then continued breaking up, leading to the present distribution of continents and oceans. The scientific community did not generally accept Wegener's ideas at first, but since the discovery of seafloor magnetic anomalies and the plate tectonic revolution, the general framework of his Pangaea model has proved to be generally valid.

The Pangaean supercontinent began amalgamating from different continental fragments with the collision of Gondwana and Laurentia and Baltica in the Middle Carboniferous, resulting in the Alleghenian, Mauritanide, and Variscan orogenies. Final assembly of Pangaea involved the collision of the South China and Cimmerian blocks to the Paleo-Tethyan margin, resulting in the early Yanshanian and Indonesinian orogenies in the Middle to Late Triassic.

The formation of Pangaea is associated with global climate change and rapid biological evolution. The numerous collisions caused an overall thickening of the continental crust that decreased continental land area and resulted in a lowering of sea level. The uplift and rapid erosion of many carbonate rocks that had been deposited on trailing or passive margins caused a decrease in the carbonate strontium 87/strontium 86 ratios in the ocean. During the final stages of the coalescence of Pangaea, drainage systems were largely internal, erosion rates were high, and the climate, with large parts of the supercontinent lying between 15° and 30° latitude, became arid, with widespread red-bed deposition. Soon however, the effects of the erosion and burial of large amounts of carbonate and the associated drawdown of atmospheric CO_2 caused climates to rapidly cool, resulting in high-latitude glaciations.

The main glaciations of Pangaea started in the Late Devonian and Early Carboniferous, began escalating in intensity by 333 million years ago, peaked in the Late Carboniferous by 292 million years ago, and ended in the Early Permian by 272 million years ago. These glaciations resulted in major global regressions as the continental ice sheets used much of the water on the planet. Wegener, and many geologists since, used the distribution of Pangaean glacial deposits as one of the main lines of reasoning to support the idea of continental drift. If the glacial deposits of similar age are plotted on a map of the present distribution of the continents, the ice flow patterns indicate that the oceans too must have been covered. However, the planet does not hold enough water to make ice sheets

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Map showing the distribution of landmasses in the supercontinent of Pangaea so large that they can cover the entire area required if the continents have not moved. If the glacial deposits are plotted on a map of Pangaea however, they cover a much smaller area, the ice flow directions are seen to radiate outward from depocenters, and the amount of water on Earth can accommodate the total volume of ice.

Pangaea began rifting and breaking apart about 230 million years ago, with numerous continental rifts, flood basalts, and mafic dikes intruding into the continental crust. Major breakup and seafloor spreading began about 175 million years ago in the central Atlantic, when North and South America broke away from Pangaea, 165 million years ago off Somalia, and 160 million years ago off the coast of northwest Australia. Sea levels began to rise with breakup because of the increase in volume of the mid-ocean ridges that displaced seawater onto the continents, forming marine transgressions. Episodic transgressions and evaporation of seawater from restricted basins led to the deposition of thick salts in parts of the Atlantic, with some salt deposits reaching 1.2 miles (2 km) thick off the east coast of North America, Spain, and northwest Africa. Several rifts along these margins have up to 6 miles (10 kilometers) of nonmarine sandstones, shales, red beds, and volcanics associated with the breakup of Pangaea. Many are very fossiliferous, including plants, mudcracks, and even dinosaur footprints attesting to the shallow water nature of these deposits.

Breakup of the supercontinent was also associated with a dramatic climate change and high sea levels. The increased volcanism at the oceanic ridges released many gases to the atmosphere, inducing global warming, leading to a global greenhouse, ideal for carbonate production on passive or trailing continental margins.

See also PALEOZOIC; SUPERCONTINENT CYCLES.

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passive margin Continental margins that are attached to the adjacent oceanic crust and do not have a plate boundary along the margin are known as passive or trailing margins. Most parts of the east coasts of North and South America, the west coasts of Europe and Africa, and most of the coastlines of India, Antarctica, and Australia are passive margins, many of which are characterized by thick accumulations of marine carbonates, shales, and sandstones. Conditions for the formation, accumulation, and preservation of hydrocarbons are met along many passive margins, so contemporaneous and ancient passive margin sequences are the focus of intense petroleum exploration.

Trailing or passive margins typically develop from a continental rift and first form an immature passive margin, with the Red Sea being the main example present on the planet at this time. Rifting along the Red Sea began in earnest by 30 million years ago, separating Arabia from Africa. The Red Sea is characterized by uplifted rift shoulders that slope generally away from the interior of the sea, but have narrow down-dropped coastal plains where steep mountain fronts are drained by wadis (dry stream beds) with alluvial fans that form a typically narrow coastal plain. These have formed over stretched continental crust, forming many rotated fault blocks and grabens, intruded by mafic dike swarms that in some places feed extensive young volcanic fields, especially in Saudi Arabia. The center of the Red Sea, which is located in tropical to subtropical latitudes, has developed thick carbonate platforms along the stretched continental crust. As rifting and associated stretching of the continental crust proceeded, areas that were once above sea level subsided below sea level, but different parts of the Red Sea basin reached this point at different times. Together with global rises and falls of sea level, this led to episodic spilling of salty seawater into restricted basins which would then evaporate, leaving thick deposits of salt behind. As rifting continued these salts became buried beneath the carbonates, shales, and sandstones, but when salt gets buried deeply it rises buoyantly, forming salt domes that pierce overlying sediments. The movement of the salt forms broad open folds that in some places forms exceptionally good petroleum traps. Parts of the passive margins along the Red Sea are several kilometers thick and currently exhibit some of the world's best coral reefs. The center of the Red Sea is marked by steep slopes off the carbonate platforms, leading to the embryonic spreading center that is present only in southern parts of the sea. Abundant volcanism, hot black smoker vents, and active metalliferous and brine mineralization on the seafloor characterize this spreading center.

As spreading continues on passive margins, the embryonic or Red Sea stage gradually evolves into a young oceanic or mature passive margin stage where the topographic relief on the margins decreases and the ocean-to-passive-margin transition becomes very flat, forming wide coastal plains such as those along the east coast of North America. This transition is an important point in the evolution of passive margins, as it marks the change from rifting and heating of the lithosphere to drifting and cooling of the lithosphere. The cooling of the lithosphere beneath the passive margin leads to gradual subsidence, typically without the dramatic faulting that characterized the rifting and Red Sea stages of the margin's evolution. Volcanism wanes, and sedimentation on the margins evolves to exclude evaporites, favoring carbonates, mudstones, sandstones, and deltaic deposits. The overall thickness of passive margin sedimentary sequences can grow to 9 or even 12.5 miles (15–20 km), making passive margin deposits among the thickest found on Earth.

Most ancient passive margins have gone through stages of evolution similar to those described for the Red Sea, so they form a distinctive assemblage of rocks in the geological record. In general ancient passive margins can be recognized first, in that they are located on the flanks of cratons, continents, or microcontinents. The rocks of the passive margin typically overlie older continental crusts although some overlie other rock sequences such as rift deposits that record a geologic history of the margin prior to its development as a passive margin. The passive margin sequence has a geometry where initial rift phase deposits are overlain by a seaward thickening and seaward deepening wedge of sedimentary rocks, typically grading from a sandy shore facies, to an offshore muddy facies, and in cases where the climate permitted, to a carbonate platform. The passive margin sequence is flanked by deep water facies rocks that, during collisional orogenesis, may be thrust on top of the shallow water sediments of the passive margin. In some cases these thrust sheets contain slivers or large thrust sheets of oceanic crust and lithosphere known as ophiolites.

The oldest known well-preserved passive margin is the Steep Rock Lake belt, which formed between 3.0 and 2.7 billion years ago in the Superior Province of Canada, although many smaller and disrupted candidates exist elsewhere in the world including a 2.9–2.7 billion-year-old passive margin in the North China craton, and a 2.7 billion-year-old margin in Zimbabwe. Passive margins show a cyclic or episodic distribution of peak abundances through geological time, with the most abundant extant passive margins found at 1950, 550, and 0 million years ago, corresponding to times of supercontinent dispersal. The opposite is also true—times where there were relatively few passive margins, such as 1750 and 300 million years ago, correspond to times of supercontinent formation.

The present day total length of passive margins on the Earth is 64,500 miles (104,000 km), and these have an average age of 104 million years and a maximum age of 180 million years. Studies of ancient passive margins by U.S. Geological Survey geologist Dwight Bradley show that they have a mean life span of 187 million years and a maximum life span of 550 million years. Divided by age, the mean life span changes from 182 million years for the Archean and Paleoproterozoic, 211 million years for the Neoproterozoic, 145 million years for the Cambrian to Carboniferous, and 142 million years for the Carboniferous to present. Overall there is a general trend for passive margins to have a longer life span with younger geological ages, suggesting that the rate of plate tectonic processes may have been faster in Precambrian times.

See also African geology; Asian geology; continental margin; divergent plate margin processes; hydrocarbons and fossil fuels; plate tectonics; subsidence.

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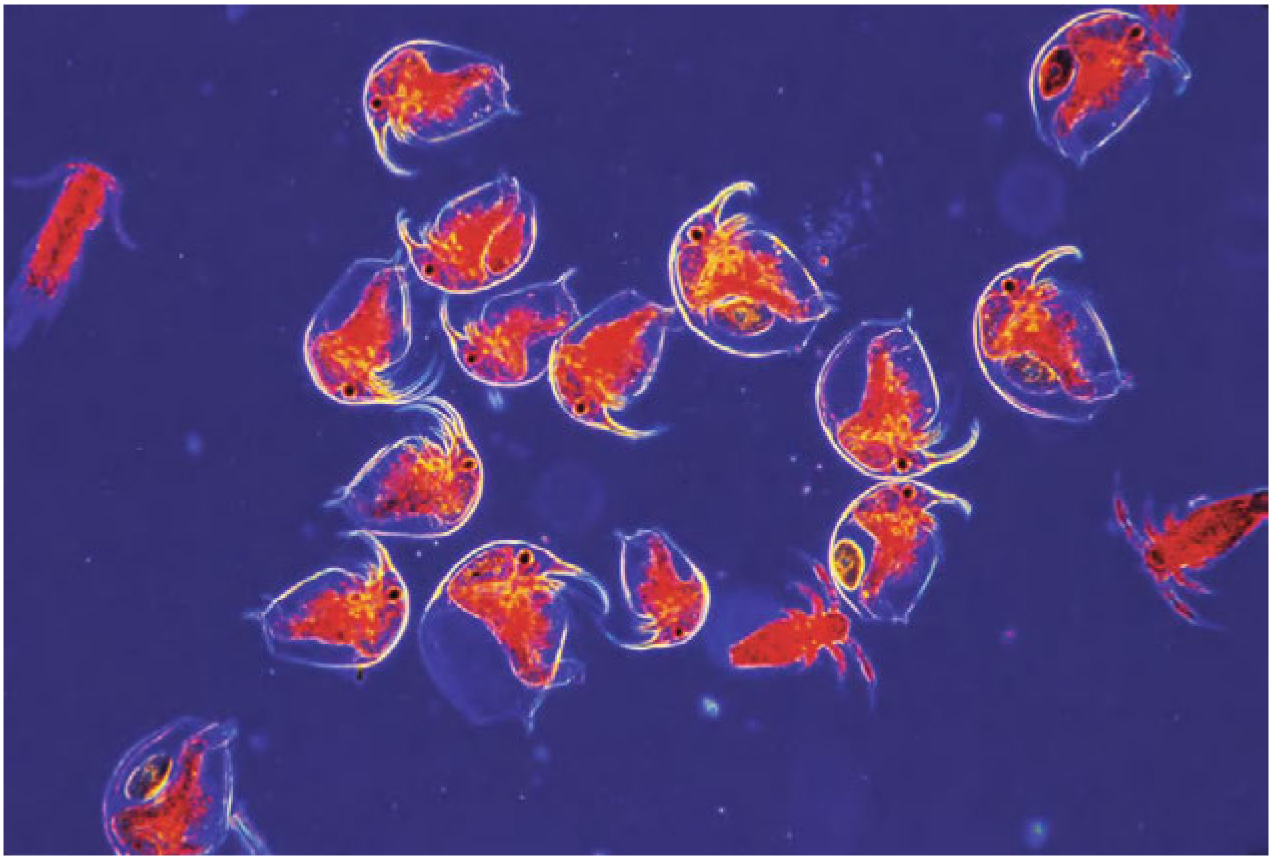
pelagic, nektonic, planktonic The pelagic environment includes the open ocean, inhabited by free-floating planktonic organisms and free-swimming nektonic organisms. Sediments that are deposited in an open ocean environment are said to be pelagic and largely consist of the remains of free-floating plankton that sink to the seafloor upon death.

Plankton, the bodies of aquatic organisms that float, drift freely, or swim weakly, includes a large variety of species in the marine realm: bacteria, phytoplankton (one-celled plantlike organisms), and zooplankton that are tiny animals such as jellyfish and invertebrates, as well as numerous nonmarine aquatic species. Planktonic species are contrasted with nektonic organisms, which are strong swimmers, and benthic organisms, which are bottom dwellers.

Planktonic species tend to be small and without strong skeletons, and they utilize the density of surrounding water to support their dominantly water-filled bodies. Many types sink or float to specific depths, where light and salinity characteristics meet their needs. They move vertically by changing the



Color-enhanced micrograph of the crustacean zooplankton *Bosmina longicornis* *(Christian Gautier/Photo Researchers, Inc.)*

amount of air in their bodies, thus getting the nutrients they require and avoiding becoming food for predators. Other plankton utilize their transparency or live in large schools of similar organisms to avoid being eaten.

Phytoplankton are microscopic floating photosynthetic organisms that form an extremely important part of the biomass and food chain. Examples include diatoms, a type of algae that secretes walls of silica; cyanobacteria, photosynthetic bacteria that have been on the Earth for at least 3.8 billion years; and dinoflagellates, flagellate protists that exhibit characteristics of both plants and animals. Coccolithophores are one-celled, floating plants covered with an armor of small calcareous plates. Silicoflagellates are similar but have plates made of silica.

Zooplankton comprises a huge variety of protozoans and small metazoans that exhibit a wide range of temperature and salinity tolerances. Some zooplankton are holoplanktonic, meaning they remain free-floating throughout their lives. In addition to phytoplankton, this group includes zooplankton such as the extremely important foraminifera that produce calcium carbonate tests and radiolaria that produce silica tests, as well as tunicates, tiny jellyfish, and copepods. Other zooplankton are considered meroplankton, meaning they spend only part of their lives as plankton, then they join either the benthic or nektonic realm. Meroplankton are common in coastal waters and include most fish eggs and the eggs and larvae of other marine animals such as marine worms or crustaceans (arthropods with stiff, chitinous outer shells or skeletons including lobsters, shrimp, crabs, and krill).

Gelatinous plankton such as jellyfish include the siphonophores that paralyze prey with stinging cells made of barbs attached to poison sacs. The siphonophores are colonies of animals that live together but function as a single animal. Ctenophores resemble jellyfish and have trailing tentacles, used to trap prey. They are carnivorous and may occur in large swarms, greatly reducing local populations of crustaceans and small or young fish. Tunicates are primitive planktonic creatures with backbones inside a barrel-shaped gelatinous structure.

Nekton are pelagic animals that move through the water primarily by swimming. Nektons are distinguished from other pelagic organisms (plankton) that float in the water. The most important nektons in the water today are the fish, whereas in the Paleozoic several other forms were common. The ammonoids of the Devonian were coiled cephalopod mollusks that evolved from earlier nautilids, and these existed with the free-swimming, scorpion-like eurypterids. Fish first appeared in the marine record in the Cambrian-Ordovician, and included the early bony-skinned fish known as ostracoderms, followed in the Late Silurian by the finned acanthodians. Heavily armored large-jawed fish known as placoderms are found in many Late Devonian deposits, as are lung fish, ray-finned fish, and lobe-finned fish that include the coelacanths, one species that survives to this day. Lobe-finned fish are the ancestors of all terrestrial vertebrates. Sharks were very common in the marine realm by the Late Paleozoic.

See also BENTHIC, BENTHOS; BIOSPHERE; FOSSIL; OCEAN BASIN; PASSIVE MARGIN.

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Permian Permian refers to the last period in the Paleozoic era, lasting from 290–248 million years ago, and to the corresponding system of rocks. Sir Roderick Murchison named it in 1841 after the Perm region of northern Russia, where rocks of this age were first studied in detail. The supercontinent of Pangaea included most of the planet's landmasses during the Permian. This continental landmass extended from the South Pole, across the equator to high northern latitudes, with a wide Tethys Sea forming an open wedge of water near the equator. The Siberian continental block collided with Laurasia in the Permian, forming the Ural Mountains. Most of Pangaea was influenced by hot and dry climate conditions and saw the formation of continental red-bed deposits and large-scale, cross-bedded sandstones, such as the Coconino sandstone of the southwestern United States and the New Red sandstone of the United Kingdom. Ice sheets covered the south-polar region, amplifying already low sea levels so they fell below the continental shelves, causing widespread mass extinctions. The glaciations continued to grow in intensity through the Permian, and together with weathering of continental calsilicates, were able to draw enough CO_2 out of the atmosphere to drastically lower global temperatures. This dramatic climate change enhanced the already widespread extinctions, killing off many species of corals, brachiopods, ammonoids, and forams in one

Fossil reptile *Orobates pabsti* Diadectomorpha Diadectidea from early Permian period. Found in the Bromacker, Germany, area *(Phil Degginger/Carnegie Museum/Alamy)* of history's greatest mass extinctions, in which about 70–90 percent of all marine invertebrate species perished, as did large numbers of land mammals. This greatest catastrophe of Earth history did not have a single cause, but reflects the combination of various elements.

The complex multi-factor cause of the end-Permian mass extinction is explained as follows. Plate tectonics was bringing many of the planet's landmasses together in a supercontinent (Pangaea), causing greater competition for fewer environmental niches by Permian life-forms. Drastically reduced were the rich continental shelf areas. As the continents collided mountains were pushed up, reducing the effective volume of the continents available to displace the sea, so sea levels fell, putting additional stress on life by further limiting the availability of favorable environmental niches. The global climate became dry and dusty, and the supercontinent formation led to widespread glaciation. This lowered sea level even more, lowered global temperatures, and put many life-forms on the planet in a very uncomfortable position, and many perished.

In the final million years of the Permian, the northern Siberian plains became the site of one of the largest volcanic effusions in Earth history. The Siberian flood basalts began erupting at 250 million years ago, becoming the largest known outpouring of continental flood basalts ever. Carbon dioxide was released in hitherto unknown abundance, warming the atmosphere and melting the glaciers. Other gases were also released, perhaps including methane, as the basalts probably melted permafrost and vaporized thick deposits of organic matter that accumulated in high latitudes like that at which Siberia was located 250 million years ago.

The global biosphere collapsed, and evidence suggests that the final collapse happened in less than 200,000 years, and perhaps in less than 30,000 years. According to this scenario, entirely internal processes may have caused the end-Permian extinction, although some scientists now argue that an impact may have dealt the final death blow. After it was over, new life-forms populated the seas and land, and these Mesozoic organisms tended to be more mobile and adept than their Paleozoic counterparts. The great Permian extinction created opportunities for new life-forms to occupy now empty niches, and the most adaptable and efficient organisms took control. The toughest of the marine organisms survived, and a new class of land animals grew to new proportions and occupied the land and skies. The Mesozoic, time of the great dinosaurs, had begun.

See also EVOLUTION; FOSSIL; MASS EXTINCTIONS; PANGAEA; STRATIGRAPHY, STRATIFICATION, CYCLOTHEM; SUPERCONTINENT CYCLES.

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petroleum geology Petroleum is a mixture of different types of hydrocarbons (fossil fuels) derived from the decomposed remains of plants and animals that are trapped in sediment, and can be used as fuel. The petroleum group of hydrocarbons includes crude oil, natural gas, and gas condensate. When plants and animals are alive, they absorb energy from the Sun (directly through photosynthesis in plants, and indirectly through consumption in animals) to make complex organic molecules. After these plants and other organisms die, if they become and remain buried before they decay, they may be converted into hydrocarbons and other fossil fuels.

Crude oil and natural gas may become concentrated in some regions and become minable for use under some special conditions. First, for oil and gas to form, more organic matter must be produced than is destroyed by scavengers and organic decay, conditions that are met in relatively few places. One of the best places for oil and gas to form is on offshore continental shelves, passive margins, or carbonate platforms, where organic productivity is high and the oxygen content of bottom waters is low, so organic decay is low and inadequate to break down the amount of organic material produced. Organic material may also be buried before it decays in sufficient quantities to make petroleum in some deltaic and continental rise environments.

Once the organic material is buried, it must reach a narrow window of specific pressure and temperature conditions to make petroleum. If these temperatures and pressures are not met or are exceeded, petroleum will not form or will be destroyed. When organic-rich rocks are in this petroleum window of

RENEWABLE ENERGY OPTIONS FOR THE FUTURE

Advanced societies require sources of external energy for transportation, heating, ventilation, production of goods, and comfort. As the world's population rapidly increases and the available supplies of economically, technologically, and environmentally extractable hydrocarbons diminishes, it is imperative that nations begin to seriously invest in developing alternative energy sources and strategies. Increased efficiency and conservation of presently known hydrocarbon reserves will help postpone the depletion of this resource, but it will eventually run out or become exceedingly expensive. To maintain levels of comfort and production in the world's civilizations, acceleration of the research and development of sustainable energy-harvesting techniques is necessary.

Primary energy sources are those that contain energy in a form (high potential) that enables them to be converted directly to lower forms of energy that are directly usable by people. These include fossil fuels, nuclear energy, and renewable resources such as biofuels, geothermal energy, hydroelectricity, solar power, tidal power, and wind power. Fossil fuels will eventually be depleted, cause significant pollution, disrupt the environment in their extraction, and emit greenhouse gases. Nuclear fuels are limited in abundance since the known resources of uranium will be depleted in dozens (uranium 235) to thousands (uranium 238) of years, and the generation of nuclear power, albeit efficient and clean, is plagued with the problem of how to dispose of the radioactive wastes. There are alternative energy sources that are renewable, clean, and efficient.

Biomass fuels involve using garbage, corn, or other vegetables to generate electricity. When garbage decomposes it generates methane that can be captured and then burned to produce electricity. Burning garbage can generate energy and alleviate land-use stress from landfills, but it also generates air pollution similar to that of burning fossil fuels. Biofuel such as vegetable oil is produced from sunlight and carbon dioxide (CO_2) by plants. It can be modified to burn like diesel fuel and is safer than gasoline since it has a higher flash point. However, the amount of plant matter required to generate biofuels is large and competes with land use for farming to feed people and livestock, driving up food prices. It also takes a significant amount of fuel to plant, fertilize, and grow biofuel stock, so some argue that there is no net gain in the biofuel economy.

Geothermal energy taps heat resources that are close to the surface in some regions of Earth, such as near volcanic centers. Less efficient geothermal sources are present in most places. Two wells are drilled in the ground; water is injected into one, and it becomes heated by the hot rocks at depth. The water is then extracted, or naturally shoots up as steam, from the other well. The energy from the steam can drive turbines to create electricity, and the heat from the water can be used as an energy source for things like home heating. Geothermal energy is cheap and generally clean, but is most efficient in specific locations where the underlying geology places hot material close to the surface.

Hydroelectricity uses the gravitational potential energy of a river by means of a dam, flume, or tunnel, using the pressure from water at high elevation to pass through a turbine or waterwheel to drive

specific temperature and pressure, organic-rich beds known as source rocks become compacted, and the organic material undergoes chemical reactions to form hydrocarbons including oil and gas. These fluids and gases have a lower density than surrounding rocks and a lower density than water, so they tend to migrate upward until they escape at the surface or are trapped between impermeable layers, where they may form a petroleum reservoir.

Oil traps are of many varieties, divided into mainly structural and stratigraphic types. Structural traps include anticlines, where the beds of rocks are folded into an upward arching dome. In these types of traps, petroleum in a permeable layer that is confined between impermeable layers (such as a sandstone bed between shale layers) may migrate up to the top of the anticlinal dome, where it becomes trapped. If a fault cuts across beds, it may form a barrier or it may act as a conduit for oil to escape, depending on the physical properties of the rock in the fault zone. In many cases faults juxtapose an oil-bearing permeable unit against an impermeable horizon, forming a structural trap. Salt domes in many places form diapirs that pierce through oil-bearing stratigraphic horizons. They typically cause an upwarping of the rock beds around the dome, forming a sort of anticlinal trap that in many regions has yielded large volumes of petroleum. Stratigraphic traps are found mainly where two impermeable layers such as shales are found above and below a lens-shaped sandstone unit that pinches out laterally to form a wedge-shaped trap. These conditions are commonly met along passive margins, where transgressions and regressions of the sea cause sand electric generators or mills. Hydroelectric plants are clean, in many cases water can be stored to be used at peak demand, and there are many undeveloped places with high potential to generate new hydroelectric power. However, construction of dams on rivers seriously affects the river dynamics and ecology, so the future of hydroelectricity may lie mostly in situations where underground tunnels can be made that utilize the gravitational potential energy, but do not seriously disrupt the river environment.

Solar power uses solar cells to convert sunlight into electricity, utilizing the most steady source of energy in the solar system. Sunlight can heat water or air in solar panels, create steam using parabolic mirrors, or be used in a more passive way, utilizing the light entering windows to heat buildings. Solar power is most efficient in places where the solar radiation is the highest. Places like the sunny desert southwestern United States are much more suited for solar power than the Pacific Northwest, which is shrouded in clouds many days of the year. Solar panels operate at different efficiencies, depending on the sunlight conditions and their construction. Assuming a 20 percent efficiency, all of the energy needs of the United States could be met if an area the size of Arizona were covered with solar panels. Solar energy requires a complementary energy storage system, since it is not available at night or during cloudy weather.

Tidal power can be harnessed by building impoundment dams that capture water at high tide and slowly release the water through turbines during low tide. Water turbines can also be located in areas with strong tidal currents, with most of the infrastructure located underwater. These turbines can be connected to electrical generators or to gas compressors, which then store the energy as compressed gas that can be slowly released to drive turbines as needed to generate electricity.

Wind power captures the energy of the wind by placing large wind turbines in persistently windy locations. The wind turns the blades of the turbines that cause the rotation of magnets that in turn generate electricity. Some locations are prone to steady and strong winds, and these locations can be the sites of wind farms where many tall towers with large blades are set up to harness the wind's power. This source of energy is clean, produces no chemical or air pollution, and is renewable. The blades of the turbines are high off the ground, so wind farms on land can function along with the primary use of the land, such as grazing or farming. Wind farms can also be placed offshore in appropriate locations; however, they can interfere with radar systems so can pose a risk to national security if placed inappropriately. Additionally, the wind is not always predictable or reliable, so wind power needs to have a storage system or be built in conjunction with other energy systems. Some communities consider wind farms to be an eyesore, and some are said to generate low-frequency noise that affects some people and animals.

The world's supply of cheap hydrocarbon reserves is running out. Examining the future trends in energy use, it is clear that many different types of renewable energy sources need to be integrated in an intelligent system that responds to local and national needs and continues to provide the energy needed for civilization's comforts and development.

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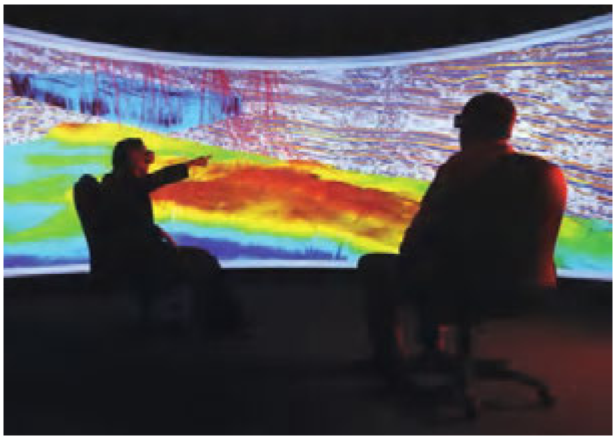
and mud facies to migrate laterally. When combined with continuous subsidence, passive margin sequences typically develop many sandstone wedges caught between shale layers. River systems and sandstone channels in muddy overbank delta deposits also form good trap and reservoir systems, since the porous sandstone channels are trapped between impermeable shales.

Most of the world's industrialized nations get the majority of their energy needs from petroleum and other fossil fuels, so exploration for and exploitation of petroleum is a major national and industrial endeavor. Huge resources are spent in petroleum exploration, and thousands of geologists are employed in the oil industry. In the early days of exploration the oil industry gained a reputation of being environmentally degrading, but increased regu-



Two geologists studying GeoProbe model. They are wearing glasses to make the model appear three-dimensional. *(Chris Sattiberger/Photo Researchers, Inc.)*

lations and awareness by these companies has greatly alleviated these problems, and most petroleum is now explored and extracted with minimal environmental consequences. The burning of fossil fuels however, continues to release huge amounts of carbon dioxide and other chemicals into the atmosphere, contributing to global warming.

See also GLOBAL WARMING; HYDROCARBONS AND FOSSIL FUELS; PASSIVE MARGIN.

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petrology and petrography Petrology is the branch of geology that attempts to describe and understand the origin, occurrence, structure, and evolution of rocks. Petrography describes the minerals and textures in rock bodies. The two fields are related but differ in that petrography is largely a descriptive science, whereas petrology uses petrographic and other data to deduce the origin and history of rocks.

Polarized light micrograph of eucrite, a type of coarse-grained gabbro from an achondritic stony meteorite, recovered from the Frankenstein-range, Hessia, Germany. Magnification: ×8 at 6×7 cm size (Alfred Pasieka/Photo Researchers, Inc.)

The petrologic classification of rocks recognizes three main categories with different modes of origin and histories. Igneous rocks crystallized from magma, and include plutonic and volcanic varieties that cooled below and at the surface, respectively. Metamorphic rocks are those that have been changed in some way, such as by the growth of new minerals or structures during heating and pressure from being subjected to tectonic forces. Sedimentary rocks include clastic varieties that represent the broken down, transported, deposited, and cemented fragments of older rocks, as well as chemical and biochemical varieties that represent chemicals that precipitated from a solution.

See also IGNEOUS ROCKS; METAMORPHISM AND METAMORPHIC ROCKS; MINERAL, MINERALOGY; SEDIMENTARY ROCK, SEDIMENTATION.

Pettijohn, Francis John (1904–1999) **American *Sedimentologist, Field Geologist*** Francis Pettijohn was born in Waterford, Wisconsin, on June 20, 1904, and is widely known as the "father of modern sedimentology." Francis became interested in geology while growing up in Bloomington, Indiana, where he often explored the many caves of the region and collected fossils from outcrops near his home. He graduated from high school in Indianapolis in 1921, then entered the University of Minnesota where he received a bachelor of arts in geology in 1924 and a master of arts, also in geology, in 1925. In 1927 he entered graduate school at the University of California at Berkeley, and then transferred to the University of Minnesota, where he received a Ph.D. in Precambrian geology in 1930. He was a professor of geology at Johns Hopkins University in Baltimore from 1952 until his retirement in 1973, and he served as chair of the department there from 1963 to 1968.

Pettijohn is most famous for his studies on the sedimentology and geological evolution of the rocks in the Appalachian Mountains and for the 24 books that he authored or coauthored. Perhaps his most famous book is *Sedimentary Rocks,* in which the techniques of modern sedimentology were clearly described, and which has been reprinted many times since its first publication in 1949. This book has remained a standard in the field for more than 50 years. Pettijohn published his own autobiography in 1984, a humorous and anecdotal work titled *Memoirs of an Unrepentant Field Geologist.*

Pettijohn received numerous awards for his work, including the Sorby Medal of the International

Francis Pettijohn in the field using magnifying lens to examine rock specimen, 1985 *(The Ferdinand Hamburger Archives, Johns Hopkins University)*

Association of Sedimentologists in 1983, the Twenhofel Medal from the Society of Economic Paleontologists and Mineralogists, the Wollaston Medal from the Geological Society of London, the Penrose Medal from the Geological Society of America, the Francis J. Pettijohn Medal from the Society for Sedimentary Geology, and an honorary doctor of science degree from the University of Minnesota. He was professionally active, serving as president of the Society of Economic Paleontologists and Mineralogists and Councilor of the Geological Society of America. Pettijohn was elected a member of the National Academy of Sciences and a Fellow of the American Academy of Arts and Sciences.

See also North American geology; sedimentary rock, sedimentation.

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Phanerozoic The eon of geological time since the base of the Cambrian at 544 million years ago and extending to the present is called the Phanerozoic. Introduced by George H. Chadwick in 1930, the eon is characterized by the appearance of abundant visible life in the geological record, in contrast to the earlier eon referred to by Chadwick as the Cryptozoic, but now generally referred to as the Precambrian. Although paleontologists now recognize that many forms of life existed prior to the Phanerozoic, the first appearance of shelly fossils corresponds to the base of the Phanerozoic.

Phanerozoic time is divided mainly on the basis of fossil correlations, and new geochronological studies of important fossil-bearing units continuously force the revision of the absolute ages for the divisions. Its three main fundamental time divisions, called eras, include the Paleozoic, Mesozoic, and Cenozoic. These eras are in turn divided into smaller divisions known as periods, epochs, and ages.

See also Cenozoic; Mesozoic; Paleozoic.

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photosynthesis Green plants, algae, and some bacteria trap solar energy and use it to drive a series of chemical reactions that results in the production of sugars, such as glucose, in a process called photosynthesis. The resulting sugars form the basic food for the plant as well as for insects and animals that eat these plants. Photosynthesis is therefore one of the most important processes for life on Earth. In order for photosynthesis to occur, the photosynthetic organisms must contain pigments such as chlorophyll. In plant cells, structures called chloroplasts contain the chlorophyll and the other necessary components. The most common type of photosynthesis also requires carbon dioxide and water and produces oxygen, also necessary for most life to exist on the planet. Before simple single-celled organisms developed the ability to carry out photosynthesis in the Precambrian, the atmosphere probably contained very little oxygen. Therefore, the process has also been largely responsible for changing the conditions on the planet's surface to make it more hospitable for the development of new, more complex life-forms and for conditions to evolve so that they are suitable for humans.

See also BIOSPHERE; ENVIRONMENTAL GEOLOGY.

planetary nebula A planetary nebula is the name for a type of emission nebula consisting of a glowing shell of gas and plasma surrounding a central core of a star that went through its hydrogen- and helium-burning stages, ejecting the outer layers of the dying giant star in one of the last stages of its evolution. The core consists of dense carbon ash, formed as a product of nuclear fusion of hydrogen and then helium, which accumulated in the core, then blew away the outer hydrogen- and helium-rich parts of the outer layers of the star as it died. Planetary nebulae have nothing to do with planets, but were named as such in the 1700s by astronomers who could observe faint blurry areas that were not as sharp as stars, and that resembled planets at the time when only crude telescopes were available. Planetary nebulae last only a few tens of thousands of years, compared to billions of years for the earlier life times of the star. Famous examples of planetary nebulae include the Cat's Eye Nebula and the Dumbbell Nebula.

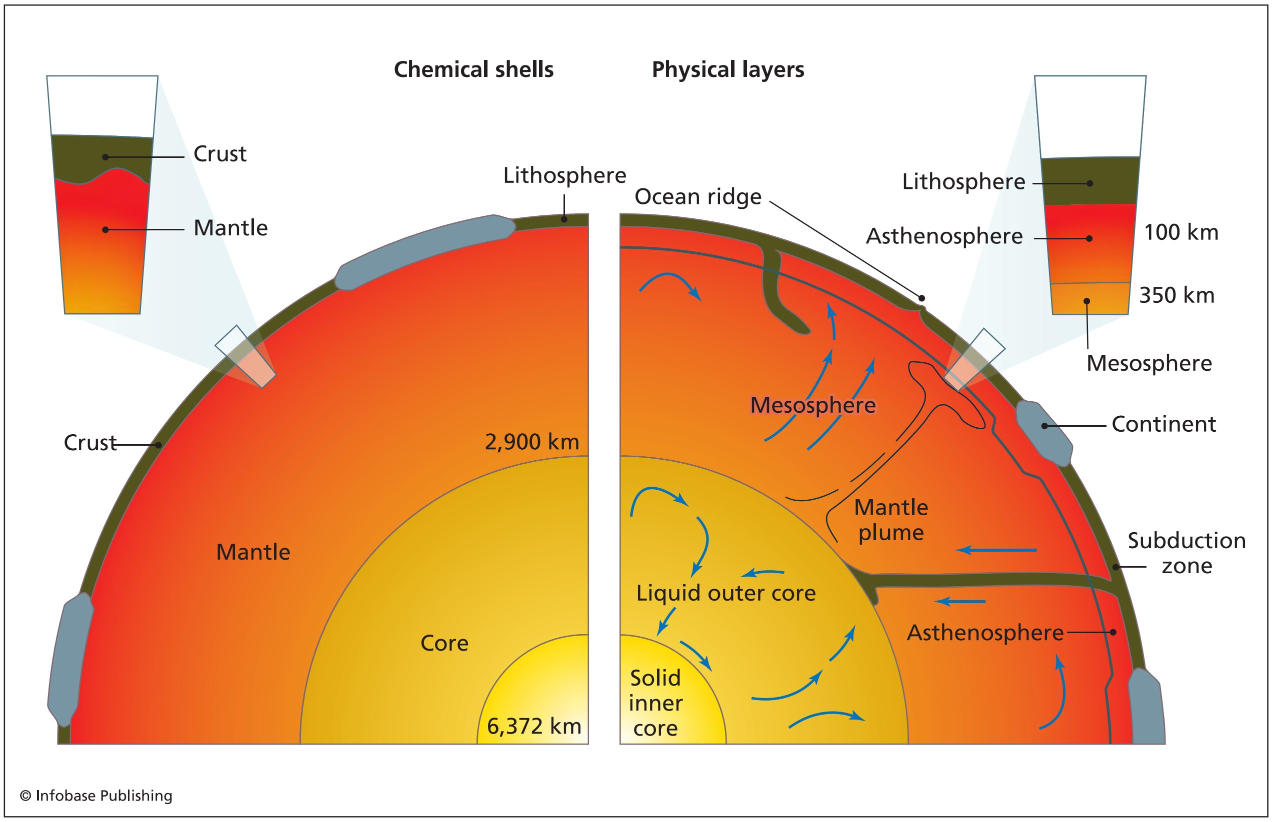
See also STELLAR EVOLUTION.

Infrared image of the Helix planetary nebula taken by *Spitzer Space Telescope,* 2/12/07. The Helix nebula is located 700 light-years away in the constellation Aquarius. Infrared light from the outer gaseous layers is represented in blues and greens, and the white dwarf star in the center is represented as a tiny white dot. The red color in the interior of the nebula is from the final layers of gas blown out as the white dwarf died. *(NASA Jet Propulsion Laboratory)*

plate tectonics The theory of plate tectonics guides the study of the large-scale evolution of the lithosphere of the Earth. In the 1960s, the Earth sciences experienced a scientific revolution, when the paradigm of plate tectonics was formulated from a number of previous hypotheses that attempted to explain different aspects about the evolution of continents, oceans, and mountain belts. New plate material is created at mid-ocean ridges and destroyed when it sinks back into the mantle in deep-sea trenches. Scientists had known for some time that the Earth is divided into many layers defined mostly by chemical characteristics, including the inner core, outer core, mantle, and crust. The plate-tectonic paradigm led to the understanding that the Earth is also divided mechanically and includes a rigid outer layer, called the lithosphere, sitting upon a very weak layer containing a small amount of partial melt of peridotite, termed the asthenosphere. The lithosphere is about 78 miles (125 km) thick under continents and 47 miles (75 km) thick under oceans, whereas the asthenosphere extends to about 155 miles (250 km) depth. The basic tenet of plate tectonics is that the outer shell or lithosphere of the Earth is broken into about twelve large rigid blocks or plates that are all moving relative to one another. These plates are torsionally rigid, meaning that they can rotate about on the surface and not deform significantly internally. Most deformation of plates occurs along their edges, where they interact with other plates.

Plate tectonics has unified the Earth sciences, bringing together diverse fields such as structural geology, geophysics, sedimentology and stratigraphy, paleontology, geochronology, and geomorphology, especially with respect to active tectonics (also known as neotectonics). Plate motion almost always involves the melting of rocks, so other fields are also important, including igneous petrology, metamorphic petrology, and geochemistry (including isotope geochemistry).

The base of the crust, known as the Mohorovicic discontinuity, is defined seismically and reflects the difference in seismic velocities of basalt and peridotite. However, the base of the lithosphere is defined on the basis of the rock's mechanical properties, as where the same rock type on either side begins to melt, and it corresponds roughly to the 2,426°F (1,330°C) isotherm. The main rock types of interest to tectonics include granodiorite, basalt, and peridotite. The average continental crustal composition is equivalent to granodiorite. (The density of granodiorite is 2.6 g/cm^3; its mineralogy includes quartz, plagioclase, biotite, and some potassium feldspar.) The average oceanic crustal composition is equivalent to that of basalt. (The density of basalt is 3.0 g/cm^3; its mineralogy includes plagioclase, clinopyroxene, and



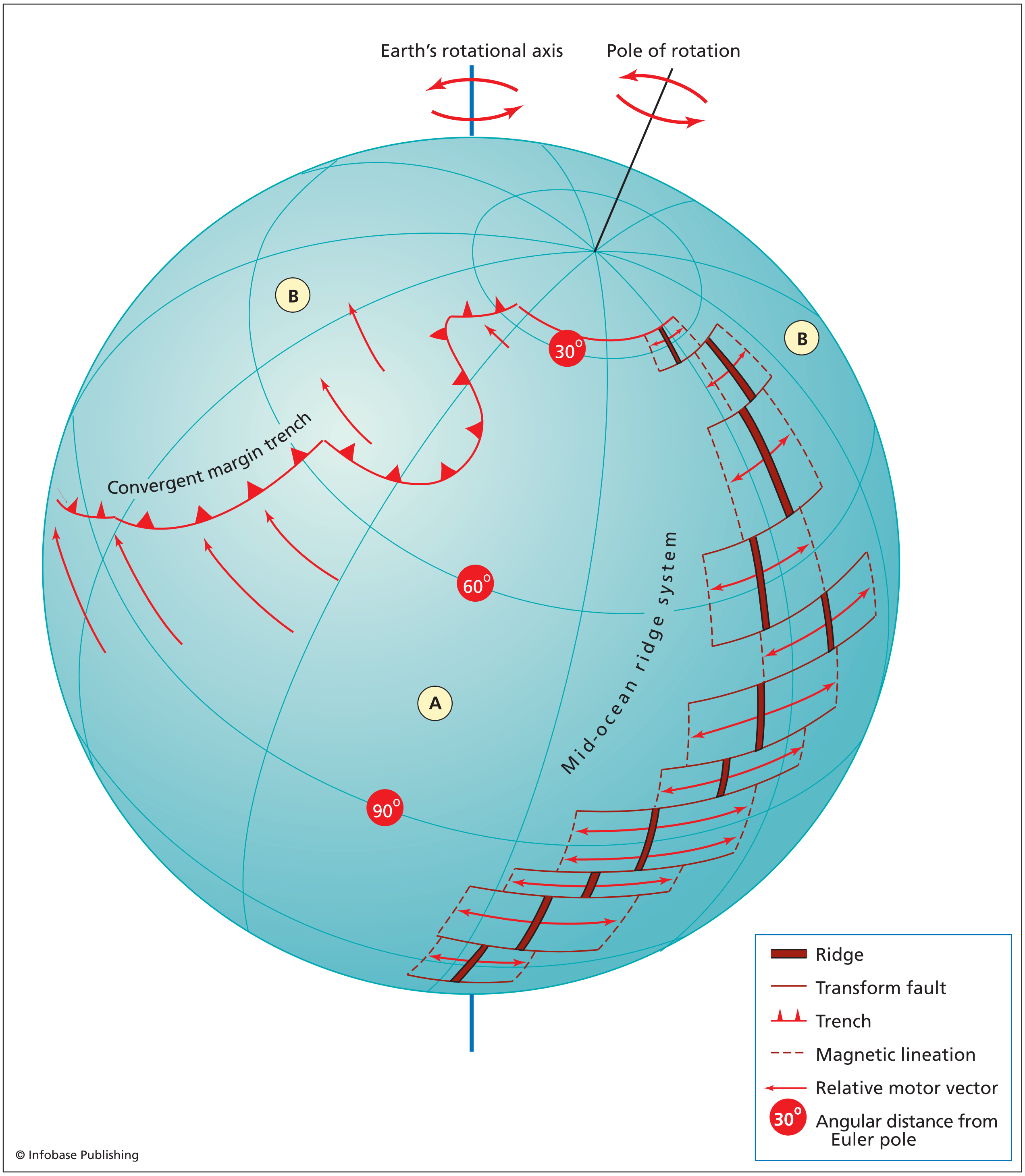
Cross sections of the Earth showing chemical shells (crust, mantle, and core) and physical layers (lithosphere, asthenosphere, mesosphere, outer core, inner core)

olivine.) The average upper mantle composition is equivalent to peridotite. (The density of peridotite is 3.3 g/cm^3; its mineralogy includes olivine, clinopyroxene, and orthopyroxene.) Considering the densities of these rock types, the crust can be thought of as floating on the mantle; rheologically, the lithosphere floats on the asthenosphere.

The plate tectonic paradigm states that the Earth's outer shell, or lithosphere, is broken into 12 large and about 20 smaller blocks, called plates, that are all moving with respect to each other. The plates are rigid, and they deform along their edges but not internally when they move. The edges of plates therefore serve as home for most of the Earth's mountain ranges and active volcanoes and are where most of the world's earthquakes occur. The plates move in response to heating of the mantle by radioactive decay and somewhat resemble lumps floating in a pot of boiling stew.

The movement of plates on the spherical Earth can be described as a rotation about a pole of rotation, using a theorem first described by Euler in 1776. Euler's theorem states that any movement of a spherical plate over a spherical surface can be described as a rotation about an axis that passes through the center of the sphere. The place where the axis of rotation passes through the surface of the Earth is referred to as the pole of rotation. The pole of rotation can be thought of as analogous to a pair of scissors opening and closing. The motions of one side of the scissors can be described as a rotation of the other side about the pin in a pair of scissors, either opening or closing the blades of the scissors. The motion of plates about a pole of rotation is described using an angular velocity. As the plates rotate, locations near the pole of rotation experience low angular velocities, whereas points on the same plates that are far from the pole of rotation experience much greater angular velocities. Therefore, oceanic-spreading rates or convergence rates along subduction zones may vary greatly along a single plate boundary. This type of relationship is similar to a marching band going around a corner. The musicians near the corner have to march in place and pivot (acting as a pole of rotation) while the musicians on the outside of the corner need to march quickly to keep the lines in the band formation straight as they go around the corner.

Rotations of plates on the Earth lead to some interesting geometrical consequences for plate tectonics. We find that mid-ocean ridges are oriented



Pole of rotation on a sphere. Plate A rotates away from Plate B, with ridge axes falling on great circles intersecting at pole of rotation and oceanic transform faults falling along small circles that are concentric about the pole of rotation. The angular velocity of the plates increases with increasing distance from the pole of rotation.

so that the ridge axes all point toward the pole of rotation and are aligned on great circles about the pole of rotation. Transform faults lie on small circles that are concentric about the pole of rotation. In contrast, convergent boundaries can lie at any angle with respect to poles of rotation.

Since plates do not deform internally, all the action happens along their edges. The type of action

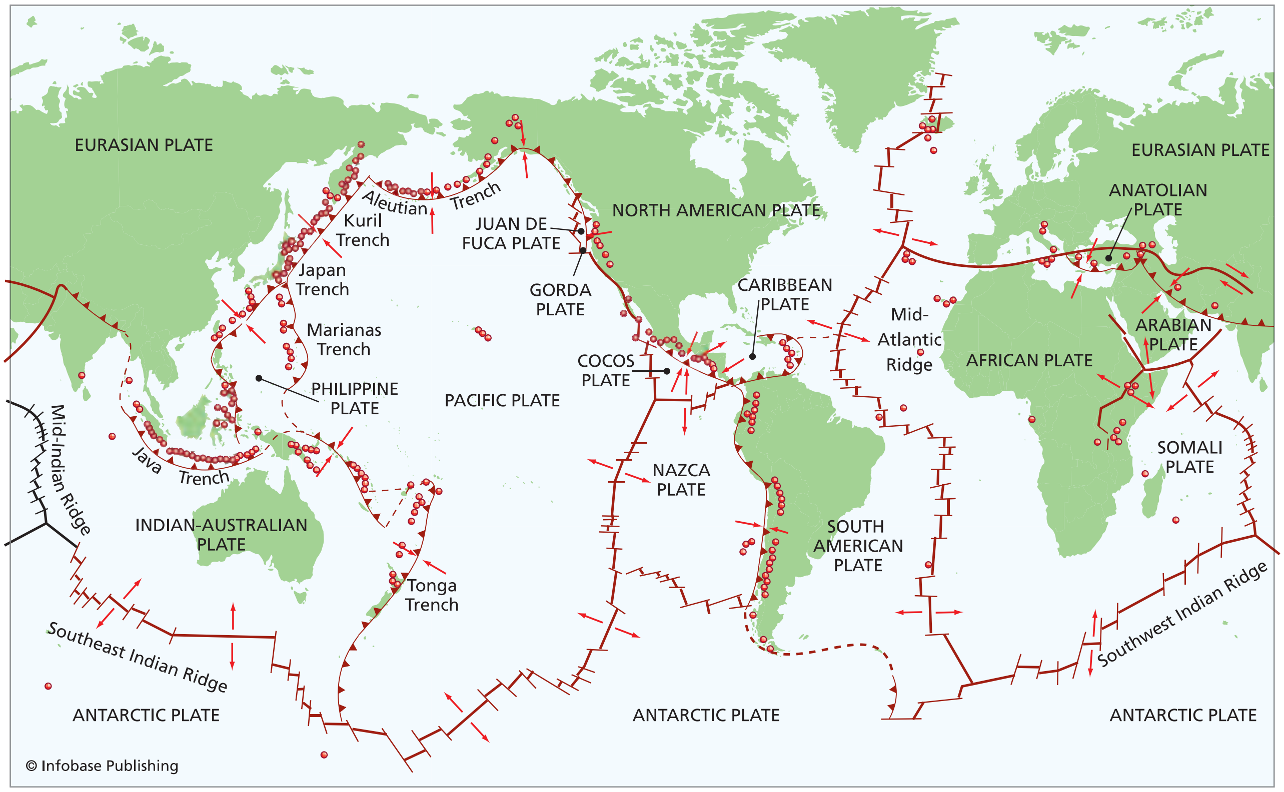


Plate tectonic map of Earth showing convergent, divergent, and transform boundaries

where two plates meet forms the basis for defining three fundamental types of plate boundaries. Divergent boundaries are where two plates move apart, creating a void that typically becomes filled by new oceanic crust that wells up to fill the progressively opening hole. Convergent boundaries are where two plates move toward each other, resulting in one plate sliding beneath the other (when a dense oceanic plate is involved), or collision and deformation (when two continental plates are involved). Transform boundaries form where two plates slide past each other, moving in opposite but parallel directions, such as along the San Andreas fault in California.

Since all plates are moving with respect to each other, the surface of the Earth is made up of a mosaic of various plate boundaries, providing geologists with an amazing diversity of different geological environments to study. Every time one plate moves, the others must move to accommodate this motion, creating a never-ending saga of different plate configurations.

DIVERGENT PLATE BOUNDARIES AND THE CREATION OF OCEANIC CRUST

Where plates diverge, seafloor spreading produces new oceanic crust. As the plates move apart, the pressure on deep underlying rocks decreases, which causes them to rise and partially melt by 15–25 percent. Basaltic magma is produced by partially melting the peridotitic mantle, leaving a "residue" type of rock in the mantle known as harzburgite. The magma produced in this way upwells from deep within the mantle to fill the gap opened by the diverging plates. This magma forms a chamber of molten or partially molten rock that slowly crystallizes to form a coarse-grained igneous rock known as gabbro, which has the same composition as basalt. Before crystallization, some of the magma moves up to the surface through a series of dikes and forms the crustal sheeted-dike complex and basaltic flows. Many of the basaltic flows have distinctive forms with the magma forming bulbous lobes known as pillow lavas. Lava tubes are also common, as are fragmented pillows formed by the implosion of the lava tubes and pillows. Back in the magma chamber, other crystals grow in the gabbroic magma, including olivine and pyroxene, which are heavier than the magma and sink to the bottom of the chamber. These crystals form layers of dense minerals known as cumulates. Beneath the cumulates, the mantle material from which the magma was derived becomes progressively more deformed as the plates diverge, forming a highly deformed ultramafic rock known as a harzburgite or mantle tectonite. This process can be seen on the surface in Iceland along the Reykjanes Ridge.

TRANSFORM PLATE BOUNDARIES AND TRANSFORM FAULTS

In many places in the oceanic basins, the mid-ocean ridges are apparently offset along great escarpments or faults, which fragment the oceanic crust into many different segments. In 1965 J. Tuzo Wilson correctly interpreted these not as offsets, but as a new class of faults, known as transform faults. The actual sense of displacement on these faults is opposite to the apparent offset, so the offset is apparent, not real. The solution to the real vs. apparent offsets along the transform faults is a primary feature of Wilson's model, proven correct by earthquake studies.

These transform faults are steps in the plate boundary where one plate is sliding past the other plate. Transform faults are also found on some continents, with the most famous examples being the San Andreas fault, the Dead Sea Transform, the North Anatolian fault, and the Alpine fault of New Zealand. All of these are large strike-slip faults with horizontal displacements and separate two different plates.

CONVERGENT PLATE BOUNDARIES

Oceanic lithosphere is being destroyed by sinking back into the mantle at the deep ocean trenches in a process called subduction. As the oceanic slabs sink downward, they experience higher temperatures that cause the release of water and other volatiles from the subducting slab, generating melts in the mantle wedge overlying the subducting slab. These melts then move upward to intrude the overlying plate, where the magma may become contaminated by melting through and incorporating minerals and elements from the overlying crust. Since subduction zones are long narrow zones where large plates are being subducted into the mantle, the melting produces a long line of volcanoes above the down-going plate. These volcanoes form a volcanic arc, either on a continent or over an oceanic plate, depending on which type of crust the overlying plate is composed of.

Island arcs are extremely important for understanding the origin of the continental crust because the magmas and sediments produced here have the same composition as the average continental crust. A simple model for the origin of the continental crust is that it represents a bunch of island arcs which formed at different times and which collided during plate collisions.

Since the plates are in constant motion, island arcs, continents, and other terranes often collide with each other. Mountain belts or orogens typically mark the places where lithospheric plates have collided, and the zone that they collided along is referred to as a suture. Suture zones are complex and include folded and faulted sequences of rocks that form on the two colliding terranes and in any intervening ocean basin. Often, slices of the old ocean floor are caught in these collision zones (these are called ophiolites), and the process by which they are emplaced over the continents is called obduction (opposite of subduction).

In some cases, subduction brings two continental plates together and they collide, forming huge mountain belts like the Himalayan Mountain chain. In continent-continent collisions, deformation may be very diffuse and extend beyond the normal limit of plate boundary deformation that characterizes other types of plate interactions. For instance, the India-Asia collision has formed the huge uplifted Tibetan Plateau, a series of mountain ranges to the north including the Tien Shan and Karakoram, and deformation of the continents extends far into Asia, as far as Lake Baikal.

HISTORICAL DEVELOPMENT OF THE PLATE TECTONIC PARADIGM

The plate tectonic paradigm was developed from a number of different models, ideas and observations that were advanced over the prior century by a number of scientists on different continents. Between 1912 and 1925, Alfred Wegener, a German meteorologist, published a series of papers and books outlining his ideas for the evolution of continents and oceans. Wegener was an early proponent of continental drift. He looked for a driving mechanism to move continents through the mantle, and invoked an imaginary force (which he called *Pohlflucht*) that he proposed caused the plates to drift toward the equator because of the rotation of the Earth. Geophysicists showed that this force was unrealistic, and since Wegener's idea of continental drift lacked a driving mechanism, it was largely disregarded.

In 1929 British geologist Arthur Holmes proposed that the Earth produces heat by radioactive decay and that there are not enough volcanoes to remove all this heat. He proposed that a combination of volcanic heat loss and mantle convection can disperse the heat, and that the mantle convection drives continental drift. Holmes wrote a textbook on this subject, which became widely used and respected. Holmes proposed that the upwelling convection cells were in the ocean basins, and that downwelling areas could be found under Andean-type volcano chains.

Alex du Toit was a South African geologist who worked on Gondwana stratigraphy and published a series of important papers between 1920 and 1940. Du Toit compared stratigraphic sections on the various landmasses that he thought were once connected to form the supercontinent of Gondwana (Africa, South America, Australia, India, Antarctica, Arabia). He showed that the stratigraphic columns of these places were very similar for the periods he proposed the continents were linked, supporting his idea of an older, large, linked landmass. Du Toit also dem-

Map of central and eastern Asia collision showing the wide area affected by the collision of India with Asia

onstrated that the floral distributions had belts that matched when the continents were reconstructed, but that appeared disjointed in the continents' present distribution.

In the 1950s, paleomagnetism began developing as a science. The Earth has a dipolar magnetic field, with magnetic field lines plunging into and out of the Earth at the north and south magnetic poles. Field or flux lines are parallel or inclined to the surface at intermediate locations, and the magnetic field can be defined by the inclination of the field lines and their deviation from true north (declination) at any location. When igneous rocks solidify, they pass through a temperature at which any magnetic minerals will preserve the ambient magnetic field at that time. In this way, some rocks acquire a magnetism when they solidify. The best rocks for preserving the ambient magnetic field are basalts, which contain 1–2 percent magnetite; they acquire a remnant inclination and declination as they crystallize. Other rocks, including sedimentary red beds with iron oxide and hematite cements, shales, limestones, and plutonic rocks, also may preserve the magnetic field, but they are plagued with other problems hindering interpretation.

In the late 1950s, British geophysicist Stanley K. Runcorn and Canadian geologist Earl Irving first worked out the paleomagnetism of European rocks and discovered a phenomenon they called apparent polar wandering (APW). The Tertiary rocks showed very little deviation from the present pole, but rocks older than Tertiary showed a progressive deviation from the expected results. They initially interpreted this to mean that the magnetic poles wandered around the planet, and the paleomagnetic rock record reflected this wandering. Runcorn and Irving made an APW path for Europe by plotting the apparent position of the pole while holding Europe stationary. However, they found that they could also interpret their results to mean that the poles were stationary and the continents were drifting around the globe. Additionally, they found that their results agreed with some previously hard to interpret paleolatitude indicators from the stratigraphy.

Next, Runcorn and Irving determined the APW curve for North America. They found it similar to Europe's from the late Paleozoic to the Cretaceous, implying that the two continents were connected for that time period and moved together, and later (in the Cretaceous) separated, as the APW curves diverged. This remarkable data set converted Runcorn from a strong disbeliever of continental drift into a drifter.

In 1954 Hugo Benioff, an American seismologist, studied worldwide, deep-focus earthquakes to about a 435 mile (700 km) depth. He plotted earthquakes on cross sections of island arcs and found earthquake foci were concentrated in a narrow zone beneath each arc, extending to about a 435 mile (700 km) depth. He noted that volcanoes of the island-arc systems were located about 62 miles (100 km) above this zone. He also noted compression in island-arc geology and proposed that island arcs are overthrusting oceanic crust. Geologists now recognize that this narrow zone of seismicity is the plate boundary between the subducting oceanic crust and the overriding island arc, and they have named this area the Benioff Zone.

Development of technologies associated with World War II led to remarkable advancements in understanding some basic properties of the ocean basins. In the 1950s, the ocean basin bathymetry, gravity, and magnetic fields were mapped for the U.S. Navy submarine fleet. After this, research scientists from oceanographic institutes such as Scripps, Woods Hole, and Lamont-Doherty Geological Observatory studied the immense sets of oceanographic data. As the raw data was acquired in the 1950s, the extent of the mid-ocean ridge system was recognized and documented by American geologists including Bruce Heezen, Maurice Ewing, and Harry Hess. They also documented the thickness of the sedimentary cover overlying igneous basement and showed that the sedimentary veneer is thin along the ridge system and thickens away from the ridges. Walter Pitman from Lamont-Doherty Geological Observatory in New York happened to cross the mid-oceanic ridge in the South Pacific perpendicular to the ridge and noticed the symmetry of the magnetic anomalies on either side of the ridge. In 1962 Harry Hess from Princeton proposed that the mid-ocean ridges were the site of seafloor spreading and the creation of new oceanic crust, and that Benioff Zones were sites where oceanic crust was returned to the mantle. In 1963 American geologists Fred Vine and Drummond Matthews combined Hess's idea and magnetic anomaly symmetry with the concept of geomagnetic reversals. They suggested that the symmetry of the magnetic field on either side of the ridge could be explained by conveyor-belt style formation of oceanic crust, forming and crystallizing in an alternating magnetic field, such that the basalts of similar ages on either side of the ridge would preserve the same magnetic field properties. Their model was based on earlier discoveries by a Japanese scientist, Motonori Matuyama, who in 1910 discovered recent basalts in Japan that were magnetized in a reversed field and proposed that the magnetic field of the Earth experiences reversals. Allen Cox (Stanford University) had constructed a geomagnetic reversal time scale in 1962, so it was possible to correlate the reversals with specific time periods and deduce the rate of seafloor spreading.

With additional mapping of the seafloor and the mid-ocean ridge system, the abundance of fracture zones on the seafloor became apparent with mapping of magnetic anomalies. In 1965, Canadian geologist J. Tuzo Wilson wrote a classic paper, "A New Class of Faults and Their Bearing on Continental Drift," published in *Nature*. This paper connected previous ideas, noted the real sense of offset of transform faults, and represented the final piece in the first basic understanding of the kinematics or motions of the plates. Lynn Sykes and other seismologists provided support for Wilson's model about one year later by using earthquake studies of the mid-ocean ridges. They noted that the ridge system divided the Earth into areas of few earthquakes, and that 95 percent of the earthquakes occur in narrow belts. They interpreted these belts of earthquakes to define the edges of the plates. They showed that about 12 major plates are all in relative motion to each other. Sykes and others confirmed Wilson's model, and showed that transform faults are a necessary consequence of spreading and subduction on a sphere.

See also CONVERGENT PLATE MARGIN PROCESSES; DIVERGENT PLATE MARGIN PROCESSES; GEODYNAMICS; TRANSFORM PLATE MARGIN PROCESSES.

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Pleistocene The Pleistocene is the older of two epochs of the Quaternary Period, lasting from 1.8 million years ago until 10,000 years ago, at the beginning of the Holocene epoch. Charles Lyell formally proposed the name Pleistocene in 1839, after earlier informal proposals, based on the appearance of species of North Sea mollusks in Mediterranean strata. The Pleistocene is recognized as an epoch of widespread glaciation, with glaciers advancing through much of Europe and North America and across the southern continents. Glaciers covered about 30 percent of the northern continents, most as huge ice sheets that advanced across Canada, the northern United States, and Eurasia. Smaller alpine glaciers dissected the mountain ranges, forming the glacial landforms visible today, including horns, arêtes, U-shaped valleys, and giant eskers and moraines. Some of the ice sheets were up to two miles (three kilometers) thick, acting as huge bulldozers that removed much of the soil from Canada and scraped the bedrock clean, depositing giant outwash plains in lower latitudes.

The continental ice sheets are known to have advanced and retreated several times during the Pleistocene, based on correlations of moraines, sea surface temperatures deduced from oxygen-isotope analysis of deep-sea cores, and magnetic stratigraphy. Eighteen major glacial expansions and retreats are now recognized from the past 2.4 million years, including four major glacial stages in North America. The Nebraskan glacial maximum peaked at 700,000

Protalus ramparts, dating from a late part of the last major glaciation, along the north base of Sunrise Ridge, northeast of Mount Rainier, Washington. The ramparts form when gravel and other debris fills cracks between the glacier and the canyon wall, leaving the debris behind as an elongate ridge when the glacier melts. *(USGS)* years ago, followed by the Kansan, Illinoian, and the Wisconsin maximums. Ice from the Wisconsin glacial maximum retreated from the northern United States and Canada only 11,000 years ago, and it may return in a short amount of geological time.

Many species became extinct or otherwise changed in response to the rapid climate changes during the Pleistocene. Many species lived in the climate zone close to the glacier front, including the woolly mammoth, giant versions of mammals now living in the arctic, rhinoceros, and caribou. Farther from the ice, giant deer, mastodons, dogs, cats, ground sloths, and other mammals were common. Both humans (Homo sapiens) and Neanderthals roamed through Eurasia, but anthropologists do not know the nature of the interaction between these two hominid species. Many of the giant mammals became extinct in the latter part of the Pleistocene, especially between 18,000 and 10,000 years ago. Currently considerable debate exists about the relative roles of climate change and predation by hominids in these extinctions.

See also NEOGENE; QUATERNARY; TERTIARY.

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Pluto The solar system has long been considered to have nine planets, including Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto. Pluto has been thought to be the most distant planet, and a relatively small body at roughly one-fifth the mass of the Earth's Moon, or 0.66 percent of the Earth's volume. Pluto is considerably smaller than many moons in the solar system, including Ganymede, Titan, Callisto, Io, Earth's Moon, Europa, and Triton. In 2006 the International Astronomical Union met, decided that Pluto does not meet the formal criteria of being a planet, and demoted the status of the object to that of a "dwarf planet." What happened?

Pluto has a colorful history of discovery. In the early to mid-1800s scientists noticed that the orbit of Uranus showed some unusual perturbations, hypothesized that these were due to the gravitational attraction of a more distant planet, and were able to predict where a new planet, Neptune, should be. French mathematician Urbain Le Verrier (1811–77) performed these calculations, then sent his calculation of where this planet should be to German astronomer Johann Gottfried Galle on September 23, 1846; Galle looked in this position and identified Neptune the following day, September 24, 1846. In the late 1800s further calculation showed that the orbit of Neptune was also being disturbed by something, so a search was mounted for another distant planet, dubbed planet "X." The search for planet "X" was pioneered by Percival Lowell, who founded the Lowell Astronomical Observatory in Arizona, who unsuccessfully searched the skies for this hypothesized planet from 1905 until his death in 1916. Clyde Tombaugh resumed the search in 1929 and then discovered a planet "X" in the right location on February 18, 1930. The name Pluto was suggested for "planet X" by an 11-year-old girl, Venetia Burney, and the name was adopted by a vote at the Lowell Observatory on March 24, 1930. Subsequent studies of Pluto revealed that it was a very small object, and many astronomers argued that it should not be a planet and could not have such an effect on the orbit of Neptune. In a twist of fate, later observations of the mass of Neptune by the *Voyager 2* spacecraft flyby in 1989 revealed that the mass of Neptune was overestimated by 0.5 percent, and this change was enough to explain the discrepancies in the orbits of Neptune and Uranus that initially led to the search for planet "X" (Pluto). Thus, the very reason for searching for a ninth planet was false.

Pluto is quite different from other planets. Not only is it very small compared to all other planets, but also it orbits far from the plane of the ecliptic, and it resides in the Kuiper Belt, along with objects that are about the same order of magnitude in size and mass as Pluto. Enis, an orbiting body further out than the Kuiper Belt in the scattered disk, is 27 percent larger than Pluto. Pluto is thought to be composed of 98 percent nitrogen ice, along with methane and carbon monoxide, similar to other objects, including comets, in the Kuiper belt and in the scattered disk that overlaps with the outer edge of the Kuiper belt. If Pluto were to orbit close to the Sun, it would develop a long cometary tail, and would be classified as a comet, not a planet.

With the advent of more powerful telescopes and data from space missions in the 1980s, 1990s, and 21st century, many objects with masses approaching that of Pluto have been discovered. After much debate and discussion, the International Astronomical Union proposed that planets need to be defined on the basis of three main criteria, and on August 24, 2006, adopted the following definition of a planet:

- A planet is a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and (c) has cleared the neighborhood around its orbit.

- A "*dwarf planet*" is a celestial body that (a) is in orbit around the Sun, (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, (c) has not cleared the neighborhood around its orbit, and (d) is not a satellite.
- All other objects, except satellites, orbiting the Sun shall be referred to collectively as *"Small Solar System Bodies."*

The International Astronomical Union made some further footnotes to their revised definition of a planet.

- The eight planets are: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune.
- An IAU process will be established to assign borderline objects into dwarf planet and other categories.
- These currently include most of the Solar System asteroids, most Trans-Neptunian Objects (TNOs), comets, and other small bodies.

The IAU further resolved that "Pluto is a 'dwarf planet' by the above definition and is recognized as the prototype of a new category of Trans-Neptunian Objects." Thus, after 100 years of searching for planet "X," and 76 years of considering it to be a planet since Pluto's discovery in 1930, the formerly most distant planet is now regarded as the second largest known dwarf planet in the solar system, and as just another large object in the Kuiper belt of the outer solar system.

The dwarf planet Pluto has a variable orbital distance of about 30–40 astronomical units (2.7–3.7 billion miles, or 4.4–6 billion km) from the Sun, circling once every 249 Earth years, and has a retrograde rotation period of 6.4 Earth days. It is a small body with a mass of 0.003 Earth masses, a diameter of 1,400 miles (2,250 km; only 20 percent that of Earth), and a density of 2.3 grams/cubic centimeter. It has one moon known as Charon, and it closely resembles other asteroids of the outer solar system. The large 17.2° inclination of its orbital plane with respect to the ecliptic plane supports the contention that Pluto is a captured asteroid.

The physical properties of the Pluton-Charon system suggest that it is an icy dual-asteroid system similar to some of the Jovian moons, being most similar to Neptune's moon Triton. Models for the origin of Pluto range from its being a captured icy asteroid or an escaped moon to being a remnant of material left over from the formation of the solar system. The great distance and small size of the system make it difficult to observe, and certainly as deep planetary probes explore the outer reaches of the solar system, new theories and models for the origin and evolution of this system will emerge.

See also EARTH; JUPITER; MARS; MERCURY; NEPTUNE; SATURN; SOLAR SYSTEM; URANUS; VENUS.

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Powell, John Wesley (1834–1902) American *Geologist, Explorer*

John Wesley Powell is most famous for his early explorations and geologic descriptions of the Grand Canyon and Colorado River in 1869. His expedition was the first passage through the Grand Canyon, and his explorations opened up the West to many later explorers. Powell became the second director of the U.S. Geological Survey, serving from 1881–94.

EARLY LIFE AND PERSONAL ACHIEVEMENTS

John Wesley Powell was born on March 24, 1834, in Mount Morris, New York, to Joseph and Mary Powell. His father was an impoverished preacher from England who moved his young family to Jackson, Ohio, then to Walworth County, Wisconsin, then to Boone County, Illinois. Powell attended Illinois College, then Wheaton College, and finally Oberlin College but never completed a degree. He developed deep knowledge of ancient Greek, Latin, and the natural sciences, particularly geology. This interest led him to explore the Mississippi River valley, including a trip in 1856, when he rowed from St. Anthony northeast of Minneapolis all the way to the Gulf of Mexico, south of New Orleans. The following year, in 1857, he rowed the Ohio River from Pittsburgh to St. Louis, followed by a trip in 1858 down the Illinois River and up the Mississippi River to central Iowa. These trips inspired him for his later explorations of the West and along the Colorado River and helped him be elected to the Illinois Natural History Society in 1859.

The Civil War broke out in 1861, and Powell enlisted with the Union Army as a topographer and military engineer to help abolish slavery. At the Battle of Shiloh on April 6 and 7, 1862, Powell was hit by a musket ball and lost most of one of his arms. He was later promoted to major and chief of artillery of the 17th Army Corps.

John Wesley Powell married Emma Dean in 1862. After the war has took a position as professor of geology at Illinois Wesleyan University and helped found the Illinois Museum of Natural History.

SCIENTIFIC CONTRIBUTIONS

In 1867 and 1868 Powell led a series of expeditions into the Rocky Mountains and along the Green and Colorado Rivers. His most famous expedition was in 1869, when he took nine men in four boats to explore the Colorado River and Grand Canyon. His geological observations led to the understanding that the canyon was formed by the river's gradually cutting down through the rocks of the region as the plateau was slowly uplifted. The team left Green River, Wyoming, on May 24 and entered the wild Colorado River near Moab, Utah. Powell took notes concerning the scenery and geology along the way, naming and traversing Glen Canyon, then reaching the Virgin River on August 30, 1869. One man had quit after the first month, and three more quit the expedition just before the junction with the Virgin River. Tragically, the three who abandoned the expedition at this point were killed in an ambush in the Wild West, but the perpetrators were never identified. On a second expedition along the same route, Powell completed an accurate map of the rivers, along with collecting many photographs and producing several scientific papers about the region.

Between 1874 and 1879, Powell was the director of the United States Geological and Geographical Survey of the Territories, and he led explorations into the Rocky Mountains of the southwestern regions. During these field excursions, Powell became convinced of the limits on development posed by the paucity of water in the desert southwest, and he completed many surveys of the region's water resources. In 1881 Powell became director of the U.S. Geological Survey, but he resigned in 1894 to pursue studies of the native peoples of the land.

See also FLUVIAL; GEOMORPHOLOGY; NORTH AMERICAN GEOLOGY.

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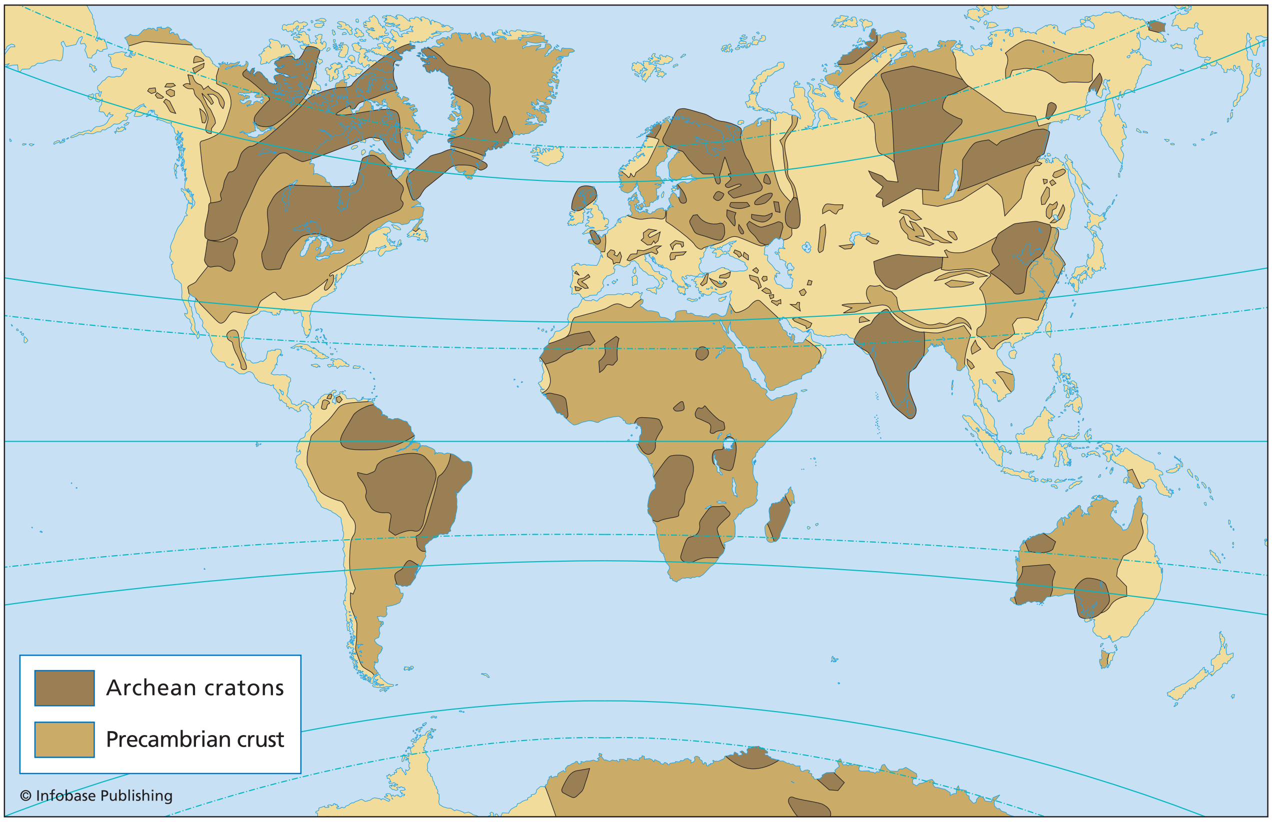
Precambrian Comprising nearly 90 percent of geologic time, the Precambrian eon includes the time interval in which all rocks older than 544 million years formed. The Precambrian is preceded by the Hadean Eon, representing the time interval during which the Earth and other planets were accreting and from which no rocks are preserved, and is succeeded by the Cambrian, the dawn of advanced life on Earth. The Precambrian consists of two eras: the Archean, ranging in age from the oldest known rocks at about 4.0 billion years old to 2.5 billion years ago, and the Proterozoic, ranging from 2.5 billion years ago until 544 million years ago. The Archean is further divided into the Early (4.0 Ga–3.0 Ga) and Late (3.0–2.5 Ga), and the Proterozoic is divided into the Early or Paleoproterozoic (2.5 Ga–1.6 Ga), Middle or Mesoproterozoic (1.6 Ga–1.3 Ga), and Late or Neoproterozoic (1.3 Ga–0.54 Ga).

Most Precambrian rocks are found in cratons, areas of generally thick crust that have been stable since the Precambrian and that exhibit low heat flow, subdued topography, and few earthquakes. Many also preserve a thick lithospheric keel known as the tectosphere. Exposed parts of Precambrian cratons are known as shields. Many of the rocks in cratons are preserved in granite-greenstone terrains, fewer are preserved as linear high-grade gneiss complexes, and still fewer form relatively undeformed sedimentary and volcanic sequences deposited in shallow water or platform basins, resting on older Precambrian rocks. Platformal sequences form a thin veneer over many older Precambrian terrains, so geologic maps of cratons and continents show many essentially flat-lying platformal units, but these are volumetrically less significant than the underlying sections of the crust. Many other areas of Precambrian rocks are found as linear tectonic blocks within younger orogenic belts. These probably represent fragments of older cratons that have been rifted, dispersed, and accreted to younger orogens by plate tectonic processes, some traveling huge distances from where they initially formed in their primary tectonic settings.

The Precambrian is the most dramatic of all geological eons, as it marks the transition from the accretion of the Earth to a planet that has plate tectonics, a stable atmosphere-ocean system, and a temperature range all delicately balanced in such a



Map of the world, showing the distribution of Precambrian rocks in Archean cratons and other undifferentiated areas of Precambrian crust

way as to allow advanced life to develop and persist on the planet. The planet has been cooling steadily since accretion and was producing more heat by radioactive decay in the Precambrian than it has been since. However, scientists do not know if this greater amount of heat significantly heated the mantle and crust, or if this additional heat was simply lost faster than it is by the present style of plate tectonics. It is likely that more rapid seafloor spreading or a greater total length of oceanic ridges with active volcanism was able to accommodate this higher heat flow, keeping mantle and crustal temperatures close to what they have been in the Phanerozoic.

Understanding of the development of life in the Precambrian has been undergoing rapid advancement, and the close links between life, atmospheric chemistry, plate tectonics, and global heat loss are only recently being explored. Many mysteries remain about the events that led to the initial creation of life, its evolution to more complex forms, and the eventual development of multi-celled complex organisms at the end of the Precambrian.

BANDED-IRON FORMATION

Banded-iron formations are a distinctive type of sedimentary rock that formed predominantly during the Precambrian and is the major source of the world's iron reserves. Banded-iron formations (BIFs) are a thinly bedded, chemically precipitated, iron-rich rock, with layers of iron ore minerals typically interbedded with thin layers of chert or microcrystalline silica. Many are completely devoid of detrital or clastic sedimentary input. Most banded-iron formations formed between 2.6 and 1.8 billion years ago, and only a few very small similar types of deposits have been discovered in younger mountain belts. This observation suggests that the conditions necessary to form the BIFs were present on Earth in early (Precambrian) time, but largely disappeared by 1.8 billion years ago. The chemical composition and reduced state of much of the iron of BIFs suggest that they may have formed in an oxygen-poor atmosphere/ocean system, explaining their disappearance around the time that atmospheric oxygen was on the rise. BIFs may also be intimately associated with early biological activity and may preserve the record of the development of life on Earth. The world's oldest BIF is located in the 3.8 billion-year-old Isua belt in southwestern Greenland, and some geologists have suggested that this formation contains chemical signatures that indicate biological activity was involved in its formation.

Two main types of banded-iron formations are classified based on the geometric and mineralogical characteristics of the deposits. Algoma-type BIFs are lens-shaped bodies that are closely associated with volcanic rocks, typically basalts. Most are around a thousand feet to several miles (several hundred meters to kilometers) in scale. In contrast, Superior-type BIFs are very large in scale, many initially covering tens of thousands of square miles (kilometers). Superior-type BIFs are closely associated with shallow marine shelf types of sedimentary rocks including carbonates, quartzites, and shales.

Banded-iron formations are also divisible into four types based on their mineralogy. Oxide-iron formations contain layers of hematite, magnetite, and chert (or cryptocrystalline silica). Silicate-iron formations contain hydrous silicate minerals including chlorite, amphibole, greenalite, stilpnomelande, and minnesotaite. Carbonate-iron formations contain siderite, ferrodolomite, and calcite. Sulfide-iron formations contain pyrite.

In addition to being rich in iron, BIFs are ubiquitously silica-rich, indicating that the water from which they precipitated was saturated in silica as well as iron. Other chemical characteristics of BIFs include low aluminum and titanium, elements that are generally increased by erosion of the continents. Therefore, BIFs are thought to have been deposited in environments away from any detrital sediment input. Some BIFs, especially the sulfide-facies Algoma-type iron formation, have chemical signatures compatible with formation near black smoker types of seafloor hydrothermal vents, whereas others may have been deposited on quiet marine platforms. In particular, many of the Superior-types of deposits have characteristics of deposition on a shallow shelf, including their association with shallow water sediments, their chemical and mineralogical constituency, and the very thin and laterally continuous nature of their layering. For instance, in the Archean Hammersley Basin of Western Australia, millimeter-thick layers in the BIF can be traced for hundreds of miles.

The environments where BIFs formed and the mechanism responsible for the deposition of the iron and silica in BIFs prior to 1.8 Ga is under current debate. Any model must explain the large-scale transport and deposition of iron and silica in thin layers, in some cases over large areas, for a limited time period of Earth's history. Some observations are pertinent. First, to form such thin layers, the iron and silica must have been dissolved in solution. For iron to be in solution, it needs to be in the ferrous (reduced) state, in turn suggesting that the Earth's early oceans and atmosphere had little if any free oxygen, and were reducing. The source of the iron and silica is also problematic; it may have come from weathering of continents or from hydrothermal vents on the seafloor. Evidence supports both ideas for individual and different kinds of BIFs, although the scales seem to be tipped in favor of hydrothermal origins for Algoma-types of deposits, and weathering of continents for Superior-type deposits.

The mechanisms responsible for causing dissolved iron to precipitate from the seawater to form the layers in banded-iron formations have also proven elusive and problematic. Changes in pH and acidity of seawater may have induced the iron precipitation, with periods of heavy iron deposition occurring during a steady background rate of silica deposition. Periods of nondeposition of iron would then be marked by deposition of silica layers. Prior to 1.8 Ga the oceans did not have organisms (e.g., diatoms) that removed silica from the oceans to make their shells, so the oceans would have been close to saturated in silica at this time, easing its deposition.

Several models have attempted to bring together the observations and requirements for the formation of banded-iron formations, but none are completely satisfactory at present. Perhaps there is no unifying model or environment of deposition, and multiple origins are possible. One model calls on alternating periods of evaporation and recharge to a restricted basin (such as a lake or playa), with changes in pH

A banded iron formation—sample is about 1 inch (2.5 cm) across *(Dirk Wiersma/Photo Researchers, Inc.)*

and acidity being induced by the evaporation. This would cause deposition of alternating layers of silica and iron. Most BIFs do not appear to have been deposited in lakes. Another model calls on biological activity to induce the precipitation of iron, but fossils and other traces of life are generally rare in BIFs, although present in some. In this model, the layers would represent daily or seasonal variations in biological activity. Another model suggests that the layering was induced by periodic mixing of an early stratified ocean, where a shallow surface layer may have had some free oxygen resulting from near-surface photosynthesis, and a deeper layer would be made of reducing waters, containing dissolved elements produced at hydrothermal seafloor vents. In this model, precipitation and deposition of iron would occur when deep reducing water upwelled onto continental shelves and mixed with oxidized surface waters. The layers in this model would then represent the seasonal (or other cycle) variation in the strength of the coastal upwelling. This last model seems most capable of explaining features of the Superior-types of deposits, such as those of the Hamersley Basin in western Australia. Variations in the exhalations of deep-sea vents may be responsible for the layering in the Algoma-type deposits. Other variations in these environments, such as oxidation, acidity, and amount of organic material, may explain the mineralogical differences between different banded-iron formations. For instance, sulfide-facies iron formations have high amounts of organic carbon (especially in associated black shales and cherts) and were therefore probably deposited in shallow basins with enhanced biological activity. Carbonate-facies BIFs have lower amounts of organic carbon and sedimentary structures indicative of shallow water deposition, so these probably were deposited on shallow shelves but farther from the sites of major biological activity than the sulfide-facies BIFs. Oxide-facies BIFs have low contents of organic carbon but have a range of sedimentary structures indicating deposition in a variety of environments.

The virtual disappearance of banded-iron formation from the geological record at 1.8 billion years ago is thought to represent a major transition on the planet from an essentially reducing atmosphere to an oxygenated atmosphere. The exact amounts and rate of change of oxygen dissolved in the atmosphere and oceans would have changed gradually, but the sudden disappearance of BIFs at 1.8 Ga seems to mark the time when the rate of supply of biologically produced oxygen overwhelmed the ability of chemical reactions in the oceans to oxidize and consume the free oxygen. The end of BIFs therefore marks the new dominance of photosynthesis as one of the main factors controlling the composition of the atmosphere and oceans.

KOMATIITE

A komatiite is a high-magnesium, ultramafic lava exhibiting spinifex (a bladed quench pattern, like ice on a window pane) textures as shown by bladed olivine or pyroxene crystals. The composition of komatiite may range from peridotite, with 30 percent MgO and 44 percent SiO_2, to basalt, with 8 percent MgO and 52 percent SiO_2. The name is from the type section on the Komati River in Barberton, South Africa. Komatiites are very rare in Phanerozoic orogenic belts and have been recovered from few places, such as fracture zones, on the modern sea floor. They are more abundant but still rare in Archean greenstone belts. Early work on komatiites suggested that they reflected high degrees of partial melting of a high temperature mantle, with mantle melting temperatures estimated to be as high as 2,912–3,272°F (1,600–1,800°C). Since these temperatures are much higher than those in the melting region of the mantle today, and since komatiites are more abundant in Archean greenstone belts than younger orogenic belts, some workers used komatiites as evidence that the Archean mantle was much hotter than the mantle is today. More recent petrological work has shown that the earlier estimates were based on dry melting experiments, and komatiites have water in their structure. Adding water to the melting calculations, new estimates of komatiite source region melting temperatures fall in the range of 2,192–2,552°F (1,200–1,400°C), much more similar to present-day mantle temperatures.

See also ARCHEAN; ATMOSPHERE; CONTINENTAL CRUST; CRATON; GREENSTONE BELTS; LIFE'S ORIGINS AND EARLY EVOLUTION; PROTEROZOIC.

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precipitation Water that falls to the surface from the atmosphere in liquid, solid, or fluid form is called precipitation. Whether it falls as rain, drizzle, fog, snow, sleet, freezing rain, or hail, it is measured as a liquid-water equivalent. The types and amounts of precipitation in different parts of the world vary greatly, from places that have never had any measurable precipitation to places that regularly receive several to more than 10 feet (hundreds of centimeters) of rain per year. Precipitation is strongly seasonal in some places, with dry and wet seasons, and distributed more regularly in other climates.

Rain is liquid precipitation with droplets greater than 0.02 inches (0.5 mm) in diameter, whereas drizzle has droplets between 0.008–0.02 inches (0.2–0.5 mm) in diameter. Fog is a cloud whose base is at the surface and has smaller particles that only truly become precipitation when wind drives them against surfaces or the ground. Freezing rain and drizzle both fall in liquid form but freeze upon hitting cold surfaces on the ground, creating a frozen coating known as glaze. Sleet consists of frozen ice pellets less than 0.2 inches (5 mm) in diameter, and hail consists of larger transparent to opaque particles that typically have diameters of 0.2–0.8 inches (5–20 mm) but sometimes are as large as golf balls or rarely even grapefruit. Snow is frozen precipitation consisting of complex hexagonal ice crystals that fall to the ground.

In tropical regions and temperate climates in warmer parts of the year, most precipitation falls as rain and drizzle. Heavy rain is defined as more than 0.16 inches (4 mm) of precipitation per hour, moderate rain falls between 0.16–0.02 inches (4 mm and 0.5 mm) per hour, and light rain (commonly called drizzle) is less than 0.02 inches (0.5 mm) per hour. Frequent and steady rains characterize some regions; others are characterized by infrequent but intense downpours, including thunderstorms that may shed hailstones. At high elevation, high latitudes, and in midlatitudes during colder months, most precipitation falls as frozen solid particles. Most frozen precipitation falls as snow that typically has a water equivalent of one-tenth the amount of snow that falls (i.e., 10 cm of snow equals 10 mm of rain). More freezing rain and sleet than snow characterize some regions, particularly coastal regions influenced by warm ocean currents.

Uplift within clouds or larger-scale systems are generally necessary to initiate the formation of water droplets that become precipitation. Convection cells in thunderheads, air forced over mountains, zones of convergence along fronts, and cyclonic systems can all produce dramatic uplift and induce precipitation. In order to form precipitation, the small water (or ice) droplets that are separated by very wide spaces must coalesce into particles large enough to fall as precipitation. Additionally, the particles must overcome the forces of evaporation as they rise or fall through unsaturated air in order to make it to the ground. Rapid lateral and vertical motions in clouds, leading to collisions between particles, aid the coalescence of particles, and gravity then accelerates particles to the ground with larger particles initially falling faster than smaller ones since they are less affected by updrafts. Large particles therefore tend to collide with and incorporate smaller particles. After frozen particles form in the upper levels of vertically extensive cloud systems, they alternately fall into and rise out of lower levels, where they partially melt, grow, and rise on updrafts. Such cycling produces relatively large particles that may fall as precipitation.

Dark storm clouds at beach *(Javarman, Shutterstock, Inc.)*

See also CLIMATE; CLIMATE CHANGE; CLOUDS; HURRICANES.

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Proterozoic The Proterozoic refers to the younger of the two Precambrian eras and the erathem of rocks deposited in this era. Divisions of the Proterozoic include the Early or Paleoproterozoic (2.5 Ga–1.6 Ga), Middle or Mesoproterozoic (1.6 Ga–1.3 Ga), and Late or Neoproterozoic (1.3 Ga–0.54 Ga). Proterozoic rocks are widespread on many continents, with large areas preserved especially well in North America, Africa and Saudi Arabia, South America, China, and Antarctica.

Like the Archean, Proterozoic terrains are of three basic types: rocks preserved in cratonic associations, orogens (often called mobile belts in Proterozoic literature), and cratonic cover associations. Wide shear zones, extensive mafic dike swarms, and layered mafic-ultramafic intrusions cut many Proterozoic terrains. Proterozoic orogens have long linear belts of arc-like associations, metasedimentary belts, and widespread, well-developed ophiolites. Many geologists believe that clear records of plate tectonics first appeared in the Proterozoic, although many others have challenged this view, placing the operation of plate tectonics earlier, in the Archean. This later view is supported by the recent recognition of Archean ophiolites (including the Dongwanzi ophiolite) in northern China.

The Proterozoic saw the development of many continental-scale orogenic belts, many of which have been recently recognized to be parts of global-scale systems that reflect the formation, breakup, and reassembly of several supercontinents. Paleoproterozoic orogens include the Wopmay in northern Canada, interpreted to be a continental margin arc that rifted from North America and then collided soon afterwards, closing the young back-arc basin. There are many 1.9–1.6 Ga orogens in many parts of the world, including the Cheyenne belt in the western United States, interpreted as a suture that marks the accretion

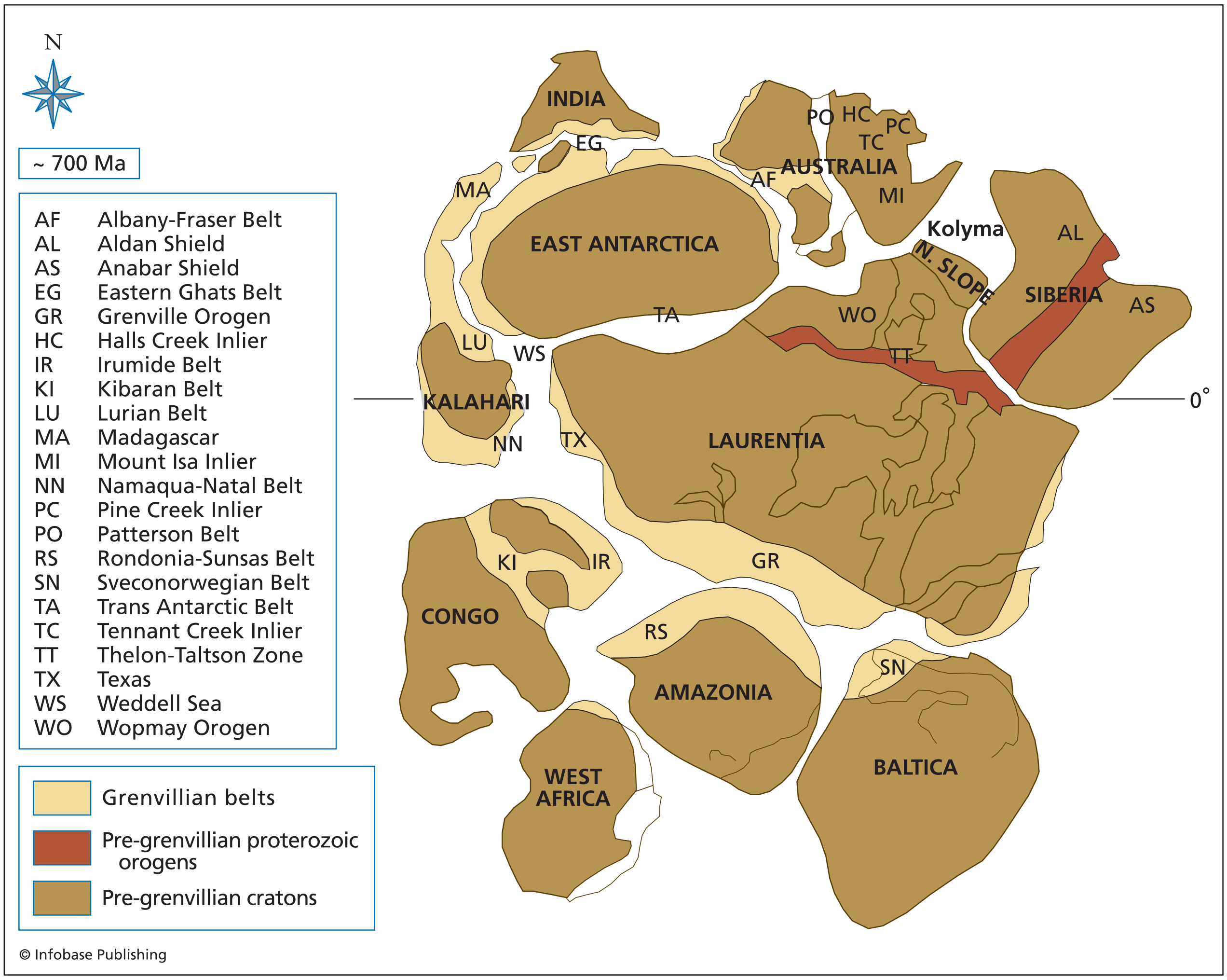

Plate reconstruction of the continents at 700 million years ago showing the supercontinent of Rodinia, with North America situated in the center of the supercontinent of the Proterozoic arc terrains of the southwestern United States with the Archean Wyoming Province.

The supercontinent Rodinia formed in Mesoproterozoic times by the amalgamation of Laurentia, Siberia, Baltica, Australia, India, Antarctica, and the Congo, Kalahari, West Africa, and Amazonia cratons between 1.1 and 1.0 Ga. The joining of these cratons resulted in the terminal collisional events at convergent margins on many of these cratons, including the ca. 1.1–1.0-Ga Ottawan and Rigolet orogenies in the Grenville Province of Laurentia's southern margin. Globally, these events have become known as the Grenville orogenic period, named after the Grenville orogen of eastern North America. Grenville-age orogens are preserved along eastern North America, as the Rodonia-Sunsas belt in Amazonia, the Irumide and Kibaran belts of the Congo craton, the Namaqua-Natal and Lurian belts of the Kalahari craton, the Eastern Ghats of India, and the Albany-Fraser belt of Australia. Many of these belts now preserve deep-crustal metamorphic rocks (granulites) that were tectonically buried to 19–25-mile- (30–40-km-) depth; then the overlying crust was removed by erosion, forcing the deeply buried rocks to the surface. Since 30–40 kilometers of crust still underlies these regions, they might have had double crustal thickness during the peak of metamorphism. Today such thick crust is produced in regions of continent-continent collision and locally in Andean arc settings. The linear quality and wide distribution of the Grenville-aged orogens suggest they delineate the sites of continent-continent collisions where the various cratonic components of Rodinia collided between 1.1 and 1.0 Ga.

The Neoproterozoic breakup of Rodinia and the formation of Gondwana at the end of the Precambrian and the dawn of the Phanerozoic represents one of the most fundamental problems being studied in earth sciences today. There have been numerous and rapid changes in the understanding of events related to the assembly of Gondwana. One of the most fundamental and most poorly understood aspects of the formation of Gondwana is the timing and geometry of closure of the oceanic basins, separating the continental fragments that amassed to form the Late Neoproterozoic supercontinent. The final collision between East and West Gondwana most likely followed the closure of the Mozambique Ocean, forming the East African Orogen, which encompasses the Arabian-Nubian shield in the north and the Mozambique Belt in the south. These and several other orogenic belts are commonly referred to as Pan-African belts, recognizing that many distinct belts in Africa and other continents experienced deformation, metamorphism, and magmatic activity spanning the period of 800–450 Ma. Pan-African tectonothermal activity in the Mozambique Belt was broadly contemporaneous with magmatism, metamorphism, and deformation in the Arabian-Nubian shield. Geologists attribute the difference in lithology and metamorphic grade between the two belts to the difference in the level of exposure, with the Mozambican rocks interpreted as lower crustal equivalents of the juvenile rocks in the Arabian-Nubian shield. Recent geochronologic data indicate the presence of two major "Pan-African" tectonic events in East Africa. The East African Orogeny (800–650 Ma) represents a distinct series of events within the Pan-African of central Gondwana, responsible for the assembly of greater Gondwana. Collectively, paleomagnetic and age data indicate that another later event at 550 Ma (Kuunga orogeny) represents the final suturing of the Australian and Antarctic segments of the Gondwana continent. The Arabian-Nubian shield in the northern part of the East African orogen preserves many complete ophiolite complexes, making it one of the oldest orogens with abundant Penrose-style ophiolites, with crustal thicknesses similar to those of Phanerozoic orogens.

The Proterozoic record preserves several continental-scale rift systems. Rift systems with associated mafic dike swarms cut across the North China craton at 2.4 and 1.8 billion years ago, as well as in many other cratons. One of the best-known of Proterozoic rifts is the 1.2–1.0-Ga Keweenawan rift, a 950-mile- (1,500-km-) long 95-mile- (150-km-) wide trough that stretches from Lake Superior to Kansas in North America. This trough, like many Proterozoic rifts, is filled with a mixture of basalts, rhyolites, arkose, conglomerate, and other, locally red, immature sedimentary rocks, all intruded by granite and syenite. Some of the basalt flows in the Keweenawan rift are 1–4 miles (2–7 km) thick.

Massive Proterozoic diabase dike swarms cut straight across many continents and may be related to some of the Proterozoic rift systems or to mantle plume activity. Some of the dike swarms are more than 1,865 miles (3,000 km) long, hundreds of kilometers wide, and consist of thousands of individual dikes ranging from less than three feet to more than 1,640 feet (1–500 m). The 1.267 Ga Mackenzie swarm of North America and others show radial patterns and point to a source near the Coppermine River basalts in northern Canada. Other dike swarms are more linear and parallel failed or successful rift arms. The direction of magma flow in the dikes is generally parallel to the surface, except in the central 300–650 miles (500–1,000 km) of the swarms, suggesting that magma may have fed upward from a plume that initiated a triple-armed rift system, and then the magma flowed away from the plume head. In some cases, such as the Mackenzie swarm, one of the rift arms succeeded in forming an ocean basin.

Arabian-Nubian shield in eastern Sudan *(Earth Sciences and Image Analysis Laboratory, NASA Johnson Space Center)*

Cratonic cover sequences are well preserved from the Proterozoic in many parts of the world. In China, the Mesoproterozoic Changcheng Series consists of several-kilometer-thick accumulations of quartzite, conglomerate, carbonate, and shale. In North America, the Paleoproterozoic Huronian Supergroup of southern Canada consists of up to 7.5 miles (12 km) of coarse clastic rocks dominated by clean beach and fluvial sandstones, interbedded with carbonates and shales. Thick sequences of continentally derived clastic rocks interbedded with marine carbonates and shales represent deposition on passive continental margins, rifted margins of back arc basins, and cratonic cover sequences from epicontinental seas. Many parts of the world have similar cratonic cover sequences, showing that continents were stable by the Proterozoic, that they were at a similar height with respect to sea level (freeboard), and that the volume of continental crust at the beginning of the Proterozoic was at least 60 percent of the present volume of continental crust.

One of the more unusual rock associations from the Proterozoic record is the 1.75–1.00 Ga granite-anorthosite association. The anorthosites (rocks consisting essentially of all plagioclase) have chemical characteristics indicating that they were derived as cumulate rocks from fractional crystallization of a basaltic magma extracted from the mantle, whereas partial melting of the lower crustal rocks produced the granites. The origin of these rocks is not clearly understood—some geologists suggest they were produced on the continental side of a convergent margin, others suggest an extensional origin, and still others suggest an anorogenic association.

Proterozoic life began with very simple organisms similar to those of the Archean, and 2.0 Ga planktonic algae and stromatolitic mounds with prokaryotic filaments and spherical forms are found in many cherts and carbonates. The stromatolites formed by cyanobacteria exhibit a wide variety of morphologies, including columns, branching columns, mounds, cones, and cauliflower type forms. In the 1960s, many geologists, particularly from the Russian academies, attempted to correlate different Precambrian strata based on the morphology of the stromatolites they contained, but this line of research proved futile as all forms are found in rocks of all ages. The diversity and abundance of stromatolites peaked about 750 million years ago, and declined rapidly after that time period, probably due to the

Stromatolites in the Helena Formation along Highline Trail, Glacier National Park, Montana *(USGS)*

sudden appearance of grazing multicellular metazoans, such as worms, at this same time. Eukaryotic cells (with membrane-bound nuclei and other distinct organelles) are preserved in sedimentary rocks from as early as 1.8 Ga, reflecting increased oxygen in the atmosphere and ocean. The acritarchs are spherical fossils of single-celled, photosynthetic marine plankton found in a wide variety of rock types. Around 750 million years ago some of the prokaryotes experienced a sudden decline, as eukaryotic life-forms adapted to fill their niches. This dramatic change is not understood, but its timing is coincident with the breakup of Rodinia and the formation of Gondwana is notable; thus tectonic changes could have induced atmospheric and environmental changes that favored one type of organism over the other.

A wide range of metazoans, complex multicellular organisms, are recognized from the geological record by 1.0 Ga, and probably evolved along several different lines before the record was well established. A few metazoans up to 1.7 Ga have been recognized from North China, but the fossil record from this interval is poorly preserved since most animals were soft-bodied. The transition from the Proterozoic fauna to the Paleozoic is marked by a remarkable group of fossils known as the Ediacaran fauna, first described from the Ediacara Hills in the Flinders Ranges of southern Australia. These 550–540 million-year-old fauna represent an extremely diverse group of multicellular, complex metazoans including jellyfishlike forms, flatwormlike forms, soft-bodied arthropods, echinoderms, and many other species. The ages of these fauna overlap slightly with the sudden appearance and explosion of shelly fauna in Cambrian strata at 540 million years ago, showing the remarkable change in life coincident with the formation of Gondwana at the end of the Proterozoic.

See also ARCHEAN; GONDWANA, GONDWANALAND; PRECAMBRIAN; SUPERCONTINENT CYCLES.

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Ptolemy, Claudius Ptolemaeus (83–168) Greek *Mathematician, Astronomer, Astrologer, Geographer*

Claudius Ptolemaeus, known in English as Ptolemy, was an important ancient Greek mathematician, astronomer, and geographer whose works contributed to building the basis for European and Islamic sciences. Ethnically Ptolemy was Greek, though his name Claudius shows he had Roman citizenship. Egyptians knew him as “The Upper Egyptian,” suggesting he was from southern Egypt, but this is not certain. His works show that he had access to the older Babylonian astronomical observations and data. He is most famous for *Almagest* (The Great Treatise, or The Mathematical Treatise). His second main work was *Geographia,* which discussed the geography of the Greco-Roman world. The third major treatise that bears Ptolemy’s name is the *Tetrabiblos* (Four Books), a discourse on astrology and natural philosophy.

Ptolemy’s *Almagest* is the oldest complete discussion of astronomy surviving from the ancient world, though older discussions are known from the Babylonian astronomers. Ptolemy claimed to have used notes from older astronomers going back more than 800 years before him in *Almagest,* yet these sources have largely disappeared with time. *Almagest* contains star tables, a star catalog, and a description of the 48 ancient constellations. Ptolemy used a geocentric model for the solar system and universe, which would be later challenged by Polish astronomer Nicolaus Copernicus, who advocated a heliocentric model. Ptolemy used a system of nested spheres to describe his geocentric model of the universe and calculated that the Sun was located 1,210 Earth radii from the Earth, while so-called fixed stars were located at 20,000 radii from the Earth, which was located at the center of the universe. *Almagest* contained a group of tables that contained the data to predict the locations of the Sun, Moon, planets, and eclipses, and these became popular. Ptolemy used them to produce a star calendar and almanac that was favored among astrologers. The popularity of *Almagest* meant that it was translated into Arabic and Latin from Greek, hence was preserved well and survives to this day.

The second main scientific work of Ptolemy was his *Geographia* (geography), a compilation of the known geographical features of the Roman Empire at the time. This included Europe and the Mediterranean area, North Africa, Arabia, Persia, and southern Asia. Many of the details of the maps shown by Ptolemy came from the earlier Greek geographer Marinos of Tyre, as well as maps from the Persians. *Geographia* contains several sections. The first includes data and methods and defines a coordinate system that included latitude measured from the equator. Ptolemy measured latitude in terms of the length of the longest day of the year at that location, which increases from 12 hours to 24 hours between the equator and the Arctic (and Antarctic) circles. For longitude Ptolemy used degrees, plotted from a meridian he placed at the westernmost known lands (Cape Verde Islands), which he called the Fortunata Islands. Ptolemy’s maps of the east show China extending southward well into the Pacific Ocean, suggesting the Greek geographers of the time knew less about Asia than about the Mediterranean. Ptolemy worked on map projections, which are ways to project the three-dimensional globe onto a two-dimensional flat map. Ptolemy’s maps appear quite distorted compared to modern maps, partly because of the primitive nature of the knowledge of the land, and partly because Ptolemy used an estimate for the size of the Earth that is much smaller than the real value.

The *Tetrabiblos,* Ptolemy’s treatise on astrology, was very popular for predicting horoscopes through celestial positions and was widely translated into Arabic and Latin. The *Tetrabiblos* was written in general terms that common people could understand. In it, Ptolemy cautioned readers to use astrology as a compilation of astronomical data and not to be overly interpretive of the numerological significance of the astronomical data as was popular at the time. Most historians suggest that Ptolemy compiled the

Tetrabiblos from earlier sources and that his main contribution was to organize it in a rational and systematic way.

Ptolemy also wrote on music, publishing *Harmonics* about the mathematics of music, suggesting that music should be based on mathematic ratios, and he demonstrated how music could be translated into mathematics. He called this technique Pythagorean tuning, after Pythagoras, who first described the relation between music and math. Ptolemy wrote about light and optics, although his works in these fields are not well preserved.

See also ASTRONOMY; CONSTELLATION; COPERNICUS, NICOLAUS; HIPPARCHUS; SOLAR SYSTEM.

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pulsar Pulsars are an unusual class of highly magnetized neutron stars that rotate quickly and emit a beam of radiation in the form of radio waves. The origin of the apparent pulsation of the beam is from the rotation of the star, and the difference between the magnetic pole of the neutron star and the rotation axis. Like the Earth, the magnetic axis of the neutron star can be offset from the rotational axis. Pulsars emit a strong beam of radiation whose direction is controlled by the orientation of the magnetic field. When the magnetic pole and the rotational pole are not coincident, the radiation beam swings wildly in space, defining a cone whose aperture is defined by the angular distance between the rotational and magnetic poles. This beam can be detected only if the beam of radiation is pointed at the observer (Earth) at one point along this cone of rotation, so there are many more pulsars in the universe than those observed from Earth. Pulsars have very regular rotation periods due to their large mass, so the observed pulses of radiation can be used as very precise clocks, with accuracies as good as atomic clocks.

The first pulsar was discovered in 1967 by Irish and British astronomers Jocelyn Bell Burnell and Antony Hewish, but the origin of the radiation was a puzzle, and some scientists even speculated that the pulses might be signals from extraterrestrial life and advanced civilizations. In 1968 Austrian astronomer Thomas Gold and his colleague Franco Pacini suggested that pulsars were rotating neutron stars. In 1974 Antony Hewish became the first astronomer to be awarded the Nobel Prize in physics, although his student Jocelyn Bell, who made the discovery while working under Hewish, was not awarded the prize. Pulsars remain a poorly understood system in the universe but those that are known fall into four distinct classes based on the source of the energy that powers the emitted radiation.

- Rotation-powered pulsars are those where the loss of rotational energy of the stars powers the radiation.
- Accretion-powered pulsars are those where the release of gravitational potential energy of infalling matter produces the energy and emits X-ray radiation.
- Magnetars are those where the decay of a tremendously strong magnetic field powers the radiation.
- Gamma ray pulsars are poorly known, but emit only gamma ray radiation.

Understanding of pulsar evolution is rapidly evolving, and some theories now suggest connections between the different types of pulsars. X-ray pulsars may be old rotation-powered pulsars that lost most of their energy and became visible again after their binary companion stars expanded and began transferring matter to the neutron star. Pulsars show an evolutionary trend, with young pulsars being fast and energetic, and old ones being slow and weak. The fastest pulsar has a period of 1.4 milliseconds, with the upper limit on rotational speed being determined by the maximum speed the neutron star can rotate at without causing the neutron-degenerate matter in its core to break up.

Observations of pulsars have been applied to many other fields in astronomy and physics. Because of the large masses and strong radiation, they have been used to test, and confirm, gravitational radiation as predicted by Einstein's theory of general relativity and aided in the first detection of an extrasolar planetary system.

See also ASTRONOMY; STELLAR EVOLUTION.

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Q

quasars Quasars are extremely powerful and distant galactic cores that are strong emitters of electromagnetic energy across the whole range of the spectrum, including X-rays, radio waves and visible light, and are associated with large redshifts, meaning that they are receding rapidly from the Earth and are located at great distances. Most quasars emit their energy almost equally across the electromagnetic spectrum, with a peak in the ultraviolet to optical bands. The name quasar is an abbreviation for QUASistellar radio source. The radiation from quasars comes from small regions, typically 10–10,000 Schwarzchild radii for the mass, which has led most astronomers to conclude that quasars represent supermassive black holes at the cores of galaxies. Being that quasars are so distant and are still observable, they must be some of the largest producers of radiation of any astronomical phenomena. Some of the more luminous quasars are more luminous than entire galaxies, emitting more radiation than a trillion stars like the Sun. The largest redshift known for any quasar is 6.43, corresponding to a distance of 28 billion light-years. This distance is seemingly impossible given the currently accepted age of the universe of 13.7 billion years, but is explained by some subtleties in the distance definitions for large distances in cosmology and general relativity. In any case, quasars are the most distant and powerful object known in the universe. Since the energy from the quasars travels to Earth at the speed of light, we know also that quasars are the oldest known objects in the universe. In many cases the radiation now being detected on Earth was emitted from the quasar shortly after the big bang.

Some quasars change rapidly in luminosity much like pulsars, particularly in the optical and X-ray bands. This observation suggests that quasars must be small objects since they cannot change faster than it takes for light to travel from one end of the object to the other. For such small objects to emit such high amounts of radiation they must use an energy source that is more efficient than the nuclear fusion that occurs in stars. The only known process that produces the required energy for sustained periods of time is the release of gravitational energy during the falling and accretion of matter to a massive star or black hole.

Quasars may be thought of as a special class of active galaxies. They are powered by release of gravitational energy during accretion of material into super massive black holes in the centers of distant galaxies. As the matter falls into the black hole it orbits the massive core, forming an accretion disk, from which much of the radiation is emitted.

There are more than 100,000 known quasars, each with a redshift between 0.06 and 6.4, which is equated with distances of 780 million to 28 billion light-years, meaning that they are among the most distant, brightest objects in the universe. Since distance is equated with time, the radiation from quasars provides a picture of what the earliest universe looked like soon after the big bang. The brightest known quasar is in the Virgo constellation and has a luminosity about 2 trillion times that of the Sun, or 100 times more than the whole Milky Way Galaxy. It would appear as bright as the Sun if it were located 33 light-years from Earth.

The fact that quasars all have large redshifts and are located at great distances from Earth means that they were more common in the early history of the universe soon after the big bang. This can be understood by considering that it takes the light billions of light years to travel from the quasars to Earth, and there are 100,000 known quasars of this old age. No quasars are known to be younger than 780 million light-years, and the further back in space/time telescopes can probe, the more abundant quasars are relative to other objects in the universe.

See also ASTRONOMY; ASTROPHYSICS; BINARY STAR SYSTEMS; BLACK HOLES; CONSTELLATION; COSMOLOGY; EINSTEIN, ALBERT; GALAXIES; HUBBLE, EDWIN; ORIGIN AND EVOLUTION OF THE UNIVERSE; PLANETARY NEBULA.

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Quaternary The last 1.8 million years of Earth history are known as the Quaternary period, which is divided into the older Pleistocene and the younger Holocene. Jules Desnoyers was the first to recognize that the rocks and unconsolidated deposits formed during this period were different from older deposits. Their characteristic boulder clays and other units deposited by glaciers in Europe reflected globally cool climates for the first part of the Quaternary, since glacier deposits were found in many parts of both the Northern and Southern Hemispheres. Global climate zones condensed near the equator, ice sheets covered about one-third of the continental surfaces, and desert regions converted to moist grasslands. Grasses, plants, and mammals experienced a rapid expansion.

Another major important discovery from this period was the recognition of the first human fossils, which became the basis for dividing the Quaternary into the older Pleistocene and the younger Holocene, in which human fossils appear abundantly about 10,000 years ago. Older primate fossils including early hominids are found in the older record going back several million years, and the record of human habitation in the Western Hemisphere extends back to approximately 13,000 or 14,000 years ago. Genetic evidence suggests that humans are all descendants of a single female ancestor that lived somewhere in East Africa about 100,000 to 300,000 years ago, with the first hominids appearing about 4 million years ago.

See also NEOGENE; PLEISTOCENE; TERTIARY.

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R

radiation Radiation refers to any process in which radiation is emitted as particles or waves (such as heat, light, alpha particles, or beta particles) from one body, travels through a medium, and is absorbed by another body. Heat transfer by infrared rays is also known as radiation or radiative heat transfer. Infrared radiation travels at the speed of light, can travel through a vacuum, gets reflected and refracted, and does not affect the medium that it passes through. Ionizing radiation occurs in processes associated with nuclear weapons and reactors and the decay of radioactive substances, whereas electromagnetic radiation refers to energy transferred through the whole range of wavelengths and frequencies, as described by the electromagnetic spectrum.

IONIZING AND NONIONIZING RADIATION

Ionizing radiation includes any radiation process in which individual quanta of energy are capable of ionizing atoms or molecules within the material that absorbs the radiation. Ionizing radiation is produced by the natural radioactive decay of rocks and radioactive materials, by cosmic rays, nuclear fission, nuclear fusion, and by similar processes that occur in nuclear weapons, nuclear reactors, X-ray equipment, and high-energy physics experiments. Ionizing radiation can cause chemical changes to the material and can damage biological tissues as well as rock and structural materials.

Particle radiation is a type of radiation that is sometimes ionizing, and sometimes not. When fast-moving subatomic particles such as electrons, protons, and neutrons carry enough energy, they produce an ionizing effect on the material through which they pass, but if their energy is too low they do not.

Nonionizing radiation is any type of radiation that does not carry enough energy per quantum to ionize atoms or molecules. In most cases nonionizing radiation consists of the lower-energy parts of the electromagnetic spectrum, including radio waves, microwaves, terahertz radiation, infrared light, and visible light. These lower-energy forms of electromagnetic radiation do not ionize or damage tissue but can excite electrons in the tissue to a higher energy state.

ELECTROMAGNETIC RADIATION

The electromagnetic spectrum categorizes types of radiation according to wavelength, with the shortest wavelengths being cosmic rays, and in increasing wavelength, gamma rays, X-rays, ultraviolet rays, visible rays, infrared rays, microwave rays, radio waves, and television waves. The environment contains a low level of constant background radiation, mostly from the radioactive decay of minerals and radioactive gases such as radon and thoron. Some background radiation, known as cosmic radiation, comes from space. The Sun emits solar radiation consisting of visible light, ultraviolet radiation, and infrared waves spanning the entire spectrum of electromagnetic wavelengths from radio waves to X-rays. The Sun also emits high-energy particles such as electrons, especially from solar flares. X-rays, because of their extremely short wavelength, are able to penetrate soft tissue and some sands and soils and reflect off internal denser material such as bones or rocks. This property has made X-rays useful for diagnostic medicine and geologic mapping of subsurface materials. Short-wavelength radiation is measured in nanometers (nm), where 1 nm equals 3.937×10^{-8} inches). Short-wavelength, high-frequency electromagnetic waves from 3.93 × 10^{-7} to 1.57 × 10^{-5} inch (10–400 nm) are known as ultraviolet radiation, which is powerful and useful to people for many applications but harmful in strong doses. Visible radiation includes all that humans see with their eyes, including the wide range of colors of the rainbow. Higher energy forms of electromagnetic radiation such as infrared, microwave, X-rays, and gamma rays can ionize materials and damage tissue.

CHARACTERISTICS OF ELECTROMAGNETIC RADIATION

Radiation from different wavelengths in the electromagnetic spectrum has very different characteristics and uses.

Radio waves have wavelengths ranging from one millimeter to hundreds of meters and frequencies of about 3 Hz to 300 GHz. They are commonly used by people to transmit data for television, mobile phones, wireless internet connections, and many other applications. The technology to encode radio waves with data is complex but involves changing the amplitude and frequency and phase relations of waves within a specific frequency band.

Microwave radiation has wavelengths ranging from one millimeter to one meter and frequencies between 0.3 GHz and 300 GHz. It includes super high frequency (SHF) and extremely high frequency classes. Microwaves are absorbed by molecules with dipolar covalent bonds, a property that is used to heat material uniformly and rapidly in microwave ovens. Microwave radiation is also used for some communication applications.

Terahertz radiation has wavelengths between the far infrared and microwaves and frequencies between 300 GHz and 3 terahertz. Radiation in this region can be used for imaging and communications and in electronic warfare to disable electronic equipment.

Infrared radiation has wavelengths between visible light and terahertz radiation and frequencies of 300 GHz (1 mm) to 400 THz (750 nm). Far-infrared radiation (300 GHz to 30 THz) is absorbed by the rotation of many gas molecules, by the molecular motions in liquids, and by phonons (a quantized mode of vibration of a crystal lattice) in solid phases. Most of the far-infrared radiation that enters the Earth's atmosphere is absorbed except for a few wavelength ranges (called windows) where some energy can penetrate. Mid-infrared radiation has frequencies from 30–120 THz and includes thermal radiation from blackbodies (i.e., bodies that absorb all energy at all wavelengths when they are cold). Near-infrared radiation is similar to visible light and has frequencies from 120 to 400 THz.

Higher frequency radiation (between 400 and 790 THz) with wavelengths between 400 and 700 nanometers is detectable by the human eye. Known as visible light, this form of radiation is also the range of most of the radiation emitted from the Sun and stars. When objects reflect or emit light in the visible range, the human eye and brain are able to process data from these wavelengths into an optical image of the object. The details of how the human brain perceives radiation from these wavelengths and processes it into an image are not completely understood. Molecular biologists, neuroscientists, psychologists, and biophysicists are actively studying these processes.

Ultraviolet radiation has wavelengths shorter than visible light and longer than X-rays, falling between 400 and 10 nm, and has energies between 3 and 124 electron volts. Ultraviolet radiation is emitted by the Sun and is a highly energetic ionizing radiation that can induce chemical reactions, may cause some substances to glow or fluoresce, and can cause sunburn on human skin. The ultraviolet radiation from the Sun is poisonous to most living organisms but is absorbed by the atmospheric ozone layer, preventing significant damage to life on Earth. If the ozone layer is depleted, ultraviolet radiation will cause significant damage to life on the surface of the Earth. During the early history of the Earth, no ozone layer existed, so the surface was constantly drenched in ultraviolet radiation. This may have prevented life from inhabiting the surface until a few billion years after the formation of the planet, when the ozone layer developed.

X-rays have wavelengths from 10 to 0.01 nanometers with frequencies between 30 petahertz and 30 exahertz (30 × 10^{15} Hz to 30 × 10^{18} Hz) and energies between 120 eV to 120 keV. X-rays can see through some objects (like flesh) but not others (like bones) and can be used to produce images for diagnostic radiography and crystallography. In the cosmos X-rays are emitted by neutron stars, some nebulae, and the accretion disks around black holes.

Gamma rays are the most energetic photons; they have no lower limit to their wavelength. Their frequency is greater than 10^{19} Hz, their energies are more than 100 keV, and their wavelengths are less than 10 picometers. Gamma rays are highly energetic and ionizing so they can cause serious damage to human tissue and represent a serious health hazard.

See also ARCHEAN; ASTRONOMY; COSMIC MICROWAVE BACKGROUND RADIATION; ELECTROMAGNETIC SPECTRUM; ENERGY IN THE EARTH SYSTEM; LIFE'S ORIGINS AND EARLY EVOLUTION; OZONE HOLE; PULSAR; QUASAR; RADIOACTIVE DECAY; RADIO GALAXIES; REMOTE SENSING.

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radioactive decay The nuclei of unstable radioactive elements spontaneously break down to become more stable, emitting radiation as alpha particles, beta particles, or gamma rays. When these particles and rays are emitted by radioactive decay, they move through matter and knock electrons out of surrounding atoms, ionizing these atoms. Alpha decay of an atomic nucleus releases heavy, slow-moving alpha particles, the most ionizing form of radioactive radiation, consisting of two neutrons and two positively charged protons. Beta decay of a nucleus converts a neutron into a proton, emitting a high-speed electron and an electron-antineutrino, increasing the atomic number by one and leaving the mass number the same. The emitted beta particles are high-speed electrons that are moderately ionizing and penetrate deeper than alpha particles. They can travel about 10 feet (several meters) in the air and are easily deflected by electromagnetic fields. Gamma rays carry no charge and are weakly ionizing; they consist of a very high frequency type of electromagnetic radiation emitted by the nuclei of radioactive elements during decay, typically as part of alpha or beta decay. Gamma rays may also form from the interaction of high-energy electrons with matter. Gamma rays are deeply penetrating, are not deflected by electromagnetic fields, and are used to kill bacteria in food or to treat malignant tumors. Space-based observatories have detected cosmic gamma radiation coming from distant pulsars, quasars, and radio galaxies, but this cosmic gamma radiation cannot penetrate the Earth's atmosphere.

When radioactive elements or radioactive isotopes of stable isotopes decay to more stable elements, the atomic mass number of the element is changed, transmuting the parent element into a different element known as a daughter isotope, emitting atomic radiation in the process. For each radioactive element or isotope, decay occurs at a constant rate known as the half-life, determined by the time taken for half of any mass of that isotope to decay from the parent isotope to the daughter isotope. Radioactive decay is an exponential process, with half of the original starting material decaying in the first step, half of the remaining material (25 percent of the original material) decaying after the second step, half of the remaining material (12.5 percent of the original material) decaying after the third step, and so on.

Radioactive decay may occur in one step, or more commonly, in a series of steps known as a decay series. In some decay series the intermediate steps may be moderately or very short-lived, and the daughter isotope may be more or less radioactive than the parent isotope. There is a very wide range in half-lives for different radioactive isotopes, ranging from 4.4 × 10^{-22} seconds for lithium 5, through 4.551 × 10^{9} years for uranium 238, to 1.5 × 10^{24} years for tellurium 128. The final product of all decay schemes is a stable element.

RADON

Radon is a poisonous gas released during radioactive decay of the uranium decay series. Radon is a heavy gas, and it presents a serious indoor hazard in every part of the country because it accumulates in poorly ventilated basements and well-insulated homes that are built on specific types of soil or bedrock rich in uranium minerals. Radon causes lung cancer, and since it is an odorless, colorless gas, its presence can go unnoticed in homes for years. However, the hazard of radon is easily mitigated, and homes can be made safe once the hazard is identified.

Uranium is a radioactive mineral that spontaneously decays to lighter daughter elements by losing high-energy particles at a predictable rate. Uranium decays to radium through a long series of steps with a cumulative half-life of 4.4 billion years. During these steps, intermediate daughter products are produced, and high-energy particles including alpha particles, consisting of two protons and two neutrons, are released, producing heat. The daughter mineral radium is itself radioactive, and it decays with a half-life of 1,620 years by losing an alpha particle, forming the heavy radon gas. Since radon is a gas, it escapes out of the minerals and ground, and makes its way to the atmosphere where it is dispersed, unless it gets trapped in people's homes, where it can cause damage by inhalation. Radon is a radioactive gas, and it decays with a half-life of 3.8 days, producing daughter products of polonium, bismuth, and lead. If this decay occurs while the gas is in someone's lungs, then the solid daughter products become lodged in the lungs, where they can cause damage. Most of the health risks from radon are associated with the daughter product polonium, which is easily lodged in lung tissue. Polonium is radioactive, and its decay and emission of high-energy particles in the lungs can damage lung tissue and eventually cause lung cancer.

Different geographic regions and specific places within those regions display huge variations in the concentration of radon. The concentration of radon gas also varies in the soil, home, and atmosphere. This variation is related to the concentration and type of radioactive elements present at a location. Radioactivity is measured in a unit known as a picocurie (pCi), which is approximately equal to the amount of radiation produced by the decay of two atoms per minute.

Soils have gases trapped between the individual grains that make up the soil, and these soil gases have typical radon levels of 20 pCi per liter to 100,000 pCi per liter, with most soils in the United States falling in the range of 200–2,000 pCi/L. Radon can also be dissolved in groundwater, with typical levels falling between 100 and 2 million pCi/L. Outdoor air typically has 0.1–20 pCi/L, and radon in the air inside people's homes ranges from 1–3,000 pCi/L, with 0.2 pCi/L being typical.

Different parts of the country and world exhibit large natural variation in radon levels. One of the main variables controlling the concentration of radon at any site is the initial concentration of the parent element uranium in the underlying bedrock and soil. If the underlying materials have high concentrations of uranium, homes built in the area are likely to have higher concentrations of radon. Most natural geologic materials contain a small amount of uranium, typically about 1–3 parts per million (ppm). The concentration of uranium in soils derived from a rock is typically about the same as in the original source rock; however, some rock (and soil) types have much higher initial concentrations of uranium, ranging up to and above 100 ppm. Granites, some types of volcanic rocks (especially rhyolites), phosphate-bearing sedimentary rocks, and the metamorphosed equivalents of all of these rocks have the highest uranium contents.

As the uranium in the soil gradually decays, it leaves behind its daughter product, radium, in concentrations proportional to the initial concentration of uranium. The radium then decays by forcefully ejecting an alpha particle from its nucleus. This ejection is an important step in the formation of radon, since every action has a reaction. In this case the reaction is the recoil of the nucleus of the newly formed radon. Most radon remains trapped in minerals once it forms. However, if the decay of radium happens near the surface of a mineral, and if the recoil of the new nucleus of radon is away from the center of the grain, the radon gas can escape the bondage of the mineral. Once free, it can move into the intergranular space between minerals, soil, or cracks in the bedrock or become absorbed in groundwater between the mineral grains. Less than half (10–50 percent) of the radon produced by decay of radium actually escapes the host mineral. Most remains trapped inside, where it eventually decays leaving the solid daughter products behind as impurities in the mineral.

Once the radon is free in the open or water-filled pore spaces of the soil or bedrock it can move rather quickly. The exact rate of movement is critical to whether or not the radon enters homes, because radon does not stay around for very long with a half-life of only 3.8 days. The rate at which radon moves through a typical soil depends on the amount of pore space in the soil (or rock), the degree of connectedness between these pore spaces, and the exact geometry and size of the openings. Radon moves slowly through less permeable materials such as clay, but quickly through porous and permeable soils such as sand and gravel, and quickly through fractured material, whether it is bedrock, clay, or concrete.

The large variation in the concentration of radon from place to place partly results from the influence of the geometry of the pore spaces in a soil or bedrock underlying a home, on the rates of movement, and also on the initial concentration of uranium in the bedrock. Homes built on dry permeable soils can accumulate radon quickly because it can migrate through the soil quickly. Conversely, homes built on impermeable soils and bedrock are unlikely to concentrate radon beyond its natural background levels.

GEOCHRONOLOGY AND THE AGE OF THE EARTH

Why do geologists say that the Earth is 4.6 billion years old? For many hundreds of years, most people in European, Western, and other cultures believed the Earth to be about 6,000 years old, based on interpretations of passages in the Torah and Old Testament. However, based on the principles of uniformitarianism outlined by James Hutton and Charles Lyell, geologists in the late 1700s and 1800s began to understand the immense amount of time required to form the geologic units and structures on the planet and argued for a much greater antiquity of the planet. When Charles Darwin advanced his ideas about evolution of species, he added his voice to those calling for tens to hundreds of millions of years required to explain the natural history of the planet and its biota. In 1846, the physicist Lord Kelvin joined the argument, but he advocated an even more ancient Earth. He noted that the temperature increased with depth, and he assumed that this heat was acquired during the initial accretion and formation of the planet and has been escaping slowly ever since. Using heat flow equations Kelvin calculated that the Earth must be 20–30 million years old. However, Kelvin assumed that there were no new inputs of heat to the planet since it formed, and he did not know about radioactivity and heat produced by radioactive decay. In 1896, Madame Curie, working in the labs of Henri Becquerel in France, exposed film to uranium in a light-tight container and found that the film became exposed by a kind of radiation that was invisible to the eye. Soon, many elements were found to have isotopes, or nucleii of the same element with different amounts of neutrons in the nucleus. Some isotopes are unstable and decay from one state to another, releasing radioactivity. Radioactive decay occurs at a very specific and fixed average rate that is characteristic of any given isotope. In 1903, Pierre Curie and Albert Laborde recognized that radioactive decay releases heat, a discovery that was immediately used by geologists to reconcile geologic evidence of uniformitarianism with Lord Kelvin's calculated age of the Earth.

In 1905, Ernest Rutherford suggested that the constant rate of decay of radioactive isotopes could be used to date minerals and rocks. Because radioactivity happens at a statistically regular rate for each isotope, it can be used to date rocks. For each isotope an average rate of decay is defined by the time that it takes half of the sample to decay from its parent to daughter product, a time known as the half-life of the isotope. Thus, to date a rock we need to know the ratio of the parent to daughter isotopes, and simply multiply by the decay rate of the parent. Half-life is best thought of as the time it takes for half of any size sample to decay, since radioactive decay is a non-linear exponential process.

The rate of decay of each isotope determines which isotopic systems can be used to date rocks of certain ages. Also, the isotopes must occur naturally in the type of rock being dated, and the daughter products must be present only from decay of the parent isotope. Some of the most accurate geochronologic clocks are made by comparing the ratios of daughter products from two different decay schemes, since both daughters are present only as a result of decay from their parents, and their ratios provide special highly sensitive clocks.

Isotopes and their decay products provide the most powerful way to determine the age of the Earth. Most elements formed during thermonuclear reactions in pre-solar system stars that experienced supernovae explosions. The main constraints we have on the age of the Earth are that it must be younger than 6–7 billion years, because it still contains elements such as K-40, with a half-life of 1.25 billion years. If the Earth were any older, all of the parent product would have decayed. Isotopic ages represent the time that that particular element-isotope system got incorporated in a mineral structure. Since isotopes have been decaying since they were incorporated, the oldest age from an Earth rock gives a minimum age of the Earth. So far, the oldest known rock is the 4.03 billion-year-old Acasta gneiss of the Slave Province in northwest Canada, and the oldest mineral is a 4.2 billion-year-old zircon from Western Australia. From these data, we can infer that the Earth is between 4.2 and 6 billion years old.

The crust on the Moon is 4.2–4.5 billion years old, and the Earth, Moon, and meteorites all formed when the solar system formed. The U-Pb isotopic system is one of the most useful for determining the age of the Earth, although many other systems give identical results. Some meteorites contain lead, but no uranium or thorium parents. Since the proportions of the various lead isotopes have remained fixed since they formed, their relative proportions can be used to measure the primordial lead ratios in the early Earth. Then, by looking at the ratios of the four lead isotopes in rocks on Earth from various ages, we can extrapolate back to when they had the same primordial lead ratio. These types of estimates give an age of 4.6–4.7 billion years for the Earth, and 4.3–4.6 billion years for meteorites. So, the best estimate for the age of the Earth is 4.6 billion years, a teenager in the universe.

See also GEOCHRONOLOGY; HUTTON, JAMES.

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radio galaxies Radio galaxies are types of active galaxies that emit large amounts of electromagnetic radiation as radio waves. They are related to other types of active galaxies including quasars, pulsars, and blazars, all of which emit the radiation through the synchrotron process. Most of the host galaxies for radio galaxies are large elliptical types, and the included radio galaxies are characterized by twin jets of material that beam strong radio-wave radiation out two opposed sides of the galaxy. Radio galaxies are used by cosmologists for calculating distances between Earth and astronomical bodies in the universe and studied for understanding processes with these unusual objects and their effects on the surrounding interstellar medium.

Emissions from radio galaxies are characterized by a smooth and polarized field, showing a broad band of distribution, so astronomers infer that the emissions are generated by the synchrotron process. Synchrotron radiation is formed by acceleration of charged particles traveling close to the speed of light in a magnetic field, so it is governed by relativistic effects described by quantum mechanics instead of the more familiar Newtonian mechanics. The material in the radio galaxies is inferred to be a plasma, or partially ionized gas in which some proportion of the electrons are free rather than bound to atoms or molecules. The charged particles that are accelerated and that emit the synchrotron radiation may be electrons, protons, or positrons. Positrons are the antiparticles, or antimatter counterparts to electrons, containing an electric charge of +1 and having the same mass as an electron. When a positron collides with an electron they annihilate each other, emitting two gamma-ray photons.

Radio galaxies show a wide range of structures when mapped using the distribution of radio-wave emissions. The most-common structure consists of lobes, which are double, generally symmetrical ellipsoidal structures extending far beyond the central nucleus of the radio galaxy. If the lobes are very elongated they are called plumes, and some radio galaxies show very thin beams known as jets that emit the radiation in narrow channels like flashlight beams at radio wavelengths. These lobes, plumes, and jets are powered by beams of high-energy particles accelerated in the nucleus of the galaxy, and they are focused by some process to form the lobe and jet structures. Radio galaxies are classified into two main types, FRI and FRII types. FRI types have the brightest emissions toward the center of the galaxy, whereas FRII types are the brightest near their edges. In general FRI types have low luminosity whereas FRII types have a high luminosity. This classification, based on morphology, also relates to the modes of energy transportation in the radio source. FRI objects transport the radiation through bright jets in the center of the galaxy, whereas FRII objects have faint jets but bright hotspots at the ends of the lobes. Energy transportation in FRII objects must be efficient to transfer the energy to the ends of the lobes, but in FRI objects the energy transportation radiates more of their energy away as it is moved along the jets.

The lobes of the largest radio galaxies extend to megaparsec scales, suggesting that it took them tens to hundreds of millions of years to grow. It is thought that the radio sources start small and grow larger gradually with time. Lobes extend from the galactic core and are fed by the jets from the cores, and as the pressure from the jets increases it causes the lobes to progressively expand. The greater the pressure exerted from the jets, the faster the lobes can expand into the interstellar medium.

Radio galaxies are commonly used by astronomers to measure large distances in the universe. Since they are so bright they can be observed from very large distances. The redshift is then measured to determine the distance to the object. Radio galaxies are being developed into a standard ruler to measure distances in the universe.

See also ASTRONOMY; ASTROPHYSICS; BLACK HOLES; COSMIC RAYS; ELECTROMAGNETIC SPECTRUM; GALAXIES; HUBBLE, EDWIN; INTERSTELLAR MEDIUM; PULSAR; QUASAR; REMOTE SENSING; TELESCOPES; UNIVERSE.

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remote sensing Remote sensing is the acquisition of information about an object by recording devices that are not in physical contact with the object. Different types include airborne or space-borne techniques and sensors that measure different properties of earth materials, ground-based sensors that measure properties of distant objects, and techniques that penetrate the ground to map subsurface properties. Common use of the term *remote sensing* refers to the airborne and space-based observation systems, with ground-based systems more commonly referred to as geophysical techniques.

Remote sensing grew out of airplane-based photogeologic reconnaissance studies, designed to give geologists a vertically downward-looking regional view of an area of interest, providing information and a perspective not readily appreciated from the ground. Many geological mapping programs include the use of stereo aerial photographs, produced by taking downward-looking photographs at regular intervals along a flight path from an aircraft, with every area on the ground covered by at least two frames. The resolution of typical aerial photographs is such that objects less than 3.2 feet (1 m) across can be easily identified. The camera and lens geometry is set so that the photographs can be viewed with a stereoscope, where each eye looks at one of the overlapping images, producing a visual display of greatly exaggerated topography. This view can be used to pick out details and variations in topography, geology, and surface characteristics that greatly aid geologic mapping. Geologic structures, rock dips, general rock types, and the distribution of these features can be mapped from aerial photographs.

Modern techniques of remote sensing employ a greater range of the electromagnetic spectrum than aerial photographs. Photographs are limited to a narrow range of the electromagnetic spectrum between the visible and infrared wavelengths that are reflected off the land's surface from the Sun's rays. Since the 1960s a wide range of sensors that can detect and measure different parts of the electromagnetic spectrum have been developed, along with a range of different optical-mechanical and digital measuring and recording devices used for measuring the reflected spectrum. In addition the establishment of many satellite-based systems has provided stable observation platforms and continuous or repeated coverage of most parts of the globe. One technique uses a mirror that rapidly sweeps back and forth across an area, measuring the radiation reflected in different wavelengths. Another technique uses a line-scanning technique, where thousands of detectors are arranged to electronically measure the reflected strength of radiation from different wavelengths in equally divided time intervals as the scanner sweeps across the surface, producing a digital image consisting of thousands of lines of small picture elements (pixels) representing each of the measured intervals. The strength of the signal for each pixel is converted to a digital number (dn) for ease of data storage and manipulation to produce a variety of different digital image products. Information from the reflected spectrum is picked up by the sensors. The digital data encodes this information, and digital image processing converts the strength of the signal from different bands into the strength of the mixture of red, green, and blue, with the mixture producing a colored image of the region. Different bands may be assigned different colors such as red, green, and blue to produce a colored image. Different electromagnetic bands may even be numerically or digitally combined or ratioed to highlight different geologic features.

Optical and infrared imagery are now widely used for regional geologic studies, with common satellite platforms including the United States–based Landsat systems, the French SPOT satellite, and more recently some multispectral sensors including Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Advanced Very High Resolution Radiometer (AVHRR) data. Optical and infrared imagery can detect differences in rock and mineral types because the reflection is sensitive to molecular interactions with solar radiation, highlighting differences between Al-OH bonds, C-O bonds, and Mg-OH bonds, effectively discriminating between different minerals such as micas, Mg-silicates, quartz, and carbonates. Bands greater than 2.4 microns are sensitive to the temperature of the surface instead of the reflected light, and studies of surface temperature have proven useful for identifying rock types, moisture content, water and hydrocarbon seeps, and caves.

Microwave remote sensing (of wavelengths less than 0.04 inches, or 1 mm) uses artificial illumination of the surface since natural emissions are too low to be useful. Satellite and aircraft-based radar systems are used to shoot energy of specific wavelength and orientation to the surface, which reflects it back to the detector. Radar remote sensing is very complex, depending on the geometry and wavelength of the system and on the nature of the surface. The strength of the received signal is dependent on features such as surface inclination, steepness, orientation, roughness, composition, and water content. Nonetheless, radar remote sensing has proven to be immensely useful for both military and scientific purposes, producing images of topography, surface roughness, and structural features such as faults, foliations, and other features that are highlighted by radar reflecting off sharp edges. Under certain circumstances, radar penetrates the surface of some geological materials (such as dry sand) and can produce images of what lies beneath the surface, including buried geologic structures, pipelines, and areas of soil moisture.

TYPES OF SATELLITE IMAGERY

Satellite imagery forms one of the basic tools for remote sensing. The types of satellite images available to the geologist, environmental scientist, and others are expanding rapidly, and only the most common in use are discussed here.

The Earth Resources Technology Satellite (ERTS-1), the first unmanned digital imaging satellite, was launched on July 23, 1972. Four other satellites from the same series, later named Landsat, were launched at intervals of a few years. The Landsat spacecraft carried a Multi-Spectral Scanner (MSS), a Return Beam Vidicon (RBV), and later, Thematic Mapper (TM) imaging systems.

Landsat Multi-Spectral Scanners produce images representing four different bands of the electromagnetic spectrum. The four bands are designated band 4 for the green spectral region (0.5 to 0.6 microns); band 5 for the red spectral region (0.6 to 0.7 microns); band 6 for the near-infrared region (0.7 to 0.8 microns); and band 7 for another near-infrared region (0.8 to 1.1 microns).

Radiation reflectance data from the four scanner channels are converted first into electrical signals, then into digital form for transmission to receiving stations on Earth. The recorded digital data are reformatted into what we know as computer compatible tapes (CCT) and/or converted at special processing laboratories to black-and-white images. These images are recorded on four black-and-white films from which photographic prints are made in the usual manner.

The black-and-white images of each band provide different sorts of information because each of the four bands records a different range of radiation. For example, the green band (band 4) most clearly shows underwater features because light with wavelengths in the green region of the visible spectrum is able to penetrate shallow water, and is therefore useful in coastal studies. The two near-infrared bands, which measure the reflectance of the Sun's rays outside the sensitivity of the human eye (visible range), are useful in the study of vegetation cover.

When these black-and-white bands are combined, false-color images are produced. For example, in the most popular combination of bands 4, 5, and 7, the red color is assigned to the near-infrared band number 7 (and green and blue to bands 4 and 5 respectively). Vegetation appears red because plant tissue is one of the most highly reflective materials in the infrared portion of the spectrum, and thus, the healthier the vegetation, the redder the color of the image. Because water absorbs nearly all infrared rays, clear water appears black on band 7. Therefore, one cannot use this band to study features beneath water even in the very shallow coastal zones, but it is useful in delineating the contact between water bodies and land areas.

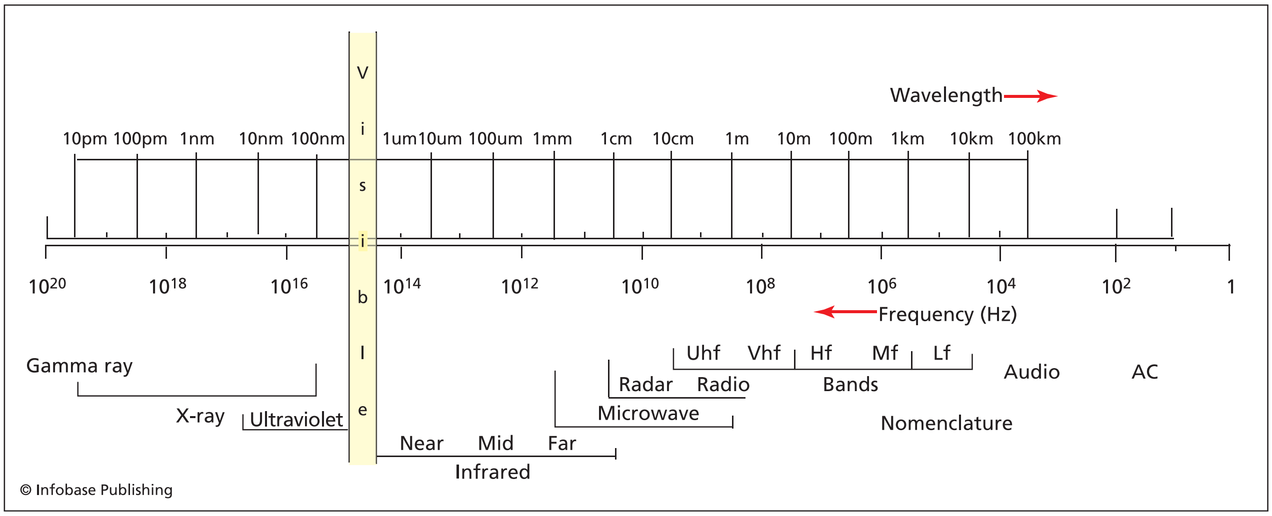
The geologic mapping community originally was most interested in flying the RBV, since it offered better geometric accuracy and ground resolution (130 feet; 40 m) than was available from the MSS (260 feet/80 m resolution) with which the RBV shared space on Landsats 1, 2, and 3. The RBV system contained three cameras that operated in different spectral bands: blue-green, green-yellow, and red-infrared. Each camera contained an optical lens, a shutter, the RBV sensor, a thermoelectric cooler, deflection and focus coils, erase lamps, and the sensor electronics. The three RBV cameras were aligned in the spacecraft to view the same 70-square-mile- (185-km^2-) ground scene as the MSS of Landsat. Although the RBV is not in operation today, images are available and can be utilized in mapping.

The TM is a sensor that was carried first on Landsat 4 and 5 with seven spectral bands covering the visible, near-infrared, and thermal infrared regions of the spectrum. With a ground resolution of 100 feet (30 m), the TM was designed to satisfy more demanding performance parameters, using experience gained from the operation of the MSS.

The seven spectral bands were selected for their band passes and radiometric resolutions. For example, band 1 of the TM coincides with the maximum transmissivity of water and demonstrates coastal water-mapping capabilities superior to those of the MSS; it also has beneficial features for the differentiation of coniferous and deciduous vegetation. Bands 2–4 cover the spectral region that is most significant for the characterization of vegetation. Band 5 readings allow estimation of vegetation and soil moisture, and thermal mapping in band 6 allows estimation of plant transpiration rates. Band 7 is primarily motivated by geological applications, including the identification of rocks altered by percolating fluids during mineralization. The band profiles, which are narrower than those of the MSS, are specified with stringent tolerances, including steep slopes in spectral response and minimal out-of-band sensitivity.

Geologic studies commonly use TM band combinations of 7 (2.08–2.35 μm), 4 (0.76–0.90 μm), and 2 (0.50–0.60 μm), due to the ability of this combination to discriminate features of interest, such as soil moisture anomalies, lithological variations, and to some extent, mineralogical composition of rocks and sediments. Band 7 is typically assigned to the red channel, band 4 to green, and band 2 to blue. This procedure results in a color composite image; the color of any given pixel represents a combination of brightness values of the three bands. With the full dynamic range of the sensors, there are 16.77×10^6 possible colors. By convention, this false-color combination is referred to as TM 742 (RGB). In addition to the TM 742 band combination, geologists sometimes use the thermal band (TM band 6; 10.4–12.5 μm) because it contains useful information potentially relevant to hydrogeology.

The French Système pour l'Observation de la Terre (SPOT) obtains data from a series of satellites in a sun-synchronous 500-mile- (830-km-) high orbit, with an inclination of 98.7°. The Centre Nationale d'Etudes Spaciales (CNES) designed the SPOT system, and the French industry in association with partners in Belgium and Sweden built it. Like the American Landsat, SPOT consists of remote-sensing satellites and ground receiving stations. The imaging is accomplished by two High-Resolution Visible (HRV) instruments that operate in either a panchromatic (black-and-white) mode for observation over a broad spectrum, or a multispectral (color) mode for sensing in narrow spectral bands. The ground resolutions are 33 and 66 feet (10 and 20 m) respectively. For viewing directly beneath the spacecraft, the two instruments can be pointed to cover adjacent areas. By pointing a mirror that directs ground radiation to the sensors, observation of any region within 280 miles (450 km) from the nadir is possible, thus



Part of the electromagnetic spectrum, showing relationship between wavelength, frequency, and nomenclature for electromagnetic radiation with different characteristics

allowing the acquisition of stereo photographs for three-dimensional viewing and imaging of scenes as frequently as every four days.

Radar is an active form of remote sensing, where the system provides a source of electromagnetic energy to illuminate the terrain. The energy returned from the terrain is detected by the same system and is recorded as a digital signal that is converted into images. Radar systems can be operated independently of light conditions and can penetrate cloud cover. A special characteristic of radar is the ability to illuminate the terrain from an optimum position to enhance features of interest.

Airborne radar imaging has been extensively used to reveal land surface features. However, until recently it has not been suitable for use on satellites because: (1) power requirements were excessive; and (2) for real-aperture systems, the azimuth resolution at the long slant ranges of spacecraft would be too poor for imaging purposes. The development of new power systems and radar techniques has overcome the first problem and synthetic-aperture radar systems have remedied the second.

The first flight of NASA's Shuttle Imaging Radar (SIR-A) in November of 1981 acquired images of a variety of features including faults, folds, outcrops, and dunes. Among the revealed features are the sand-buried channels of ancient river and stream courses in the Western Desert of Egypt. The second flight, SIR-B, had a short life; however, the more advanced and higher resolution SIR-C was flown in April 1994 (and was again utilized in August 1994). The SIR-C system measures both horizontal and vertical polarizations simultaneously at two wavelengths: L-band (23.5 cm) and C-band (5.8 cm). This provides dual frequency and dual polarization data, with a swath width between 18 and 42 miles (30 and 70 km), yielding precise data with large ground coverage.

Different combinations of polarizations are used to produce images showing much more detail about surface geometric structure and subsurface discontinuities than a single-polarization-mode image. Similarly, different wavelengths are used to produce images showing different roughness levels since radar brightness is most strongly influenced by objects comparable in size to the radar wavelength; hence, the shorter wavelength C-band increases the perceived roughness.

Interpretation of a radar image is not intuitive. The mechanics of imaging and the measured characteristics of the target are significantly different for microwave wavelengths than the more familiar optical wavelengths. Hence, possible geometric and electromagnetic interactions of the radar waves with anticipated surface types have to be assessed prior to their examination. In decreasing order of effect, these qualities are surface slope, incidence angle, surface roughness, and the dielectric constant of the surface material.

Radar is uniquely able to map the geology at the surface and, in the dry desert environments, up to a maximum 30 feet (10 m) below the surface. Radar images are most useful for mapping structural and morphological features, especially fractures and drainage patterns, as well as the texture of rock types, in addition to revealing sand-covered paleochannels. The information contained in the radar images complements that in the TM images and eliminates the limitations of Landsat when only sporadic measurements can be made; radar sensors have the ability to "see" at night and through thick cloud cover since they are active rather than passive sensors.

RADARSAT is an Earth observation satellite developed by Canada, designed to support both research on environmental change and research on resource development. It was launched in 1995 on a Delta II rocket with an expected life span of five years. RADARSAT operates with an advanced radar sensor called Synthetic Aperture Radar (SAR). The synthetic aperture increases the effective resolution of the imaged area by means of an antenna design in which the spatial resolution of a large antenna is synthesized by multiple sampling from a small antenna. RADARSAT's SAR-based technology provides its own microwave illumination, thus can operate day or night, regardless of weather conditions. Thus, resulting images are not affected by the presence of clouds, fog, smoke, or darkness. This provides significant advantages in viewing under conditions that preclude observation by optical satellites. Using a single frequency, 2-inch (5-cm) horizontally polarized C band, the RADARSAT SAR can shape and steer its radar beam to image swaths between 20 and 300 miles (35 km to 500 km), with resolutions from 33 feet to 330 feet (10 m to 100 m), respectively. Incidence angles can range from less than 20° to more than 50°.

The Space Shuttle orbiters have the capability of reaching various altitudes, which allows the selection of the required photographic coverage. A camera that was specifically designed for mapping the Earth from space using stereo photographs was first flown in October 1984 on the Space Shuttle Challenger Mission 41-G. It used an advanced, specifically designed system to obtain mapping-quality photographs from Earth orbit. This system consisted of the Large Format Camera (LFC) and the supporting Attitude Reference System (ARS). The LFC derives its name from the size of its individual frames, which are 26 inches (66 cm) in length and 9 inches (23 cm) in width. The 992-pound (450-kg) camera has a 12-inch (305-mm) f/6 lens with a 40° × 74° field of view. The film, which is three-fourths of a mile (1,200 m) in length, is driven by a forward motion compensation mechanism as it is exposed on a vacuum plate, which keeps it perfectly flat. The spectral range of the LFC is 400 to 900 nanometers, and its photo-optical ground resolution ranges from 33–66 feet (10 to 20 m) from an altitude of 135 miles (225 km) in the 34,200 square mile (57,000 km^2) area that is covered by each photograph.

The ARS is composed of two cameras with normal axes that take 35-millimeter photographs of star fields at the same instant as the LFC takes a photograph of the Earth's surface. The precisely known positions of the stars allow the calculation of the exact orientation of the Shuttle orbiter, and particularly of the LFC in the Shuttle cargo bay. This accurate orientation data, together with the LFC characteristics, allows the location of each frame with an accuracy of less than half a mile (1 km) and the making of topographic maps of photographed areas at scales of up to 1:50,000.

SYNTHETIC APERTURE RADAR

Spaceborne remotely sensed imagery has been routinely used as a reconnaissance tool by geologists since the initial launch of the Landsat series of satellites in 1972. More recently, spaceborne sensors such as Thematic Mapper (TM), Seasat Synthetic Aperture Radar (SAR), Shuttle Imaging Radar (SIR-A and SIR-B), and Système pour l'Observation de la Terre (SPOT) have scanned the Earth's surface with other portions of the electromagnetic spectrum in order to sense different features, particularly surface roughness and relief, and to improve spatial resolution. While TM and SPOT images have proven spectacularly effective at differentiating between various rock types, synthetic aperture radar (SAR) is particularly useful at delineating topographically expressed structures. Spaceborne SAR systems also play a major role in exploration of other bodies in the solar system.

Synthetic aperture radar (SAR) is an active sensor where energy is sent from a satellite (or airplane) to the surface at specific intervals in the ultrahigh frequency range of radar. The radar band refers to the specific wavelength sent by the source, and may typically include X-band (4 cm), K-band (2 cm), P-band (1 meter), L-band (23.5 cm), C-band, or others. SAR allows the user to acquire detailed images at any time of day or night and also in inclement weather. A complicated system, SAR basically works by first obtaining a two-dimensional image and then fine tuning that image with computers and sensors to create a decisively more accurate image. SAR provides detailed resolutions of a particular area for governments, military applications, and scientists, but is expensive to others who may wish to use it. The advancement of technology, however, is making it possible and economical in other applications.

The effectiveness of orbital SAR for geologic, particularly structural, studies depends primarily on three factors: (1) roughness contrasts; (2) local incidence angle variations (i.e., topography); and (3) look azimuth relative to topographic trends. Atmospheric or soil moisture can attenuate the strength of the radar signal, as can the types of atomic bonds in the minerals present in surface materials to some degree. Bodies of water are generally smoother than land, and appear as dark, radar smooth terrain. Structure is delineated on land by variations in local incidence angle, with surface roughness controlling the precise backscatter dependence. Different SAR satellites have different radar incidence or look angles, and some, such as RADARSAT, are adjustable and specifiable by the user. The 20° look angle chosen for Seasat was intended to maximize the definition of sea conditions, but had the incidental benefit of producing stronger sensitivity to terrain than would larger angles. Look azimuth has been shown to be an extremely important factor for low relief terrain of uniform roughness, with topography within about 20° of the normal to look azimuth being strongly highlighted.

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river system Stream and river valleys have served as preferred sites for human habitation for millions of years because they provide routes of easy access through rugged mountainous terrain and water for drinking, watering animals, and irrigation. Most of the world's large river valleys are located in structural or tectonic depressions such as rifts, including the Nile, Amazon, Mississippi, Hudson, Niger, Limpopo, Rhine, Indus, Ganges, Yenisei, Yangtze, Amur, and Lena. The soils in river valleys are also some of the most fertile that can be found, as they are replenished by yearly or less frequent floods. The ancient Egyptians, whose entire culture developed in the Nile River valley and revolved around the flooding cycles of the river, appreciated this characteristic of river systems. Rivers now provide easy and relatively cheap transportation on barges, and the river valleys are preferred routes for roads and railways as they are relatively flat and easier to build in than over mountains. Many streams and rivers have also become polluted as industry has dumped billions of gallons of chemical waste into our nation's waterways.

Stream and rivers are dynamic environments—their banks are prone to erosion, and the rivers periodically flood over their banks. During floods, rivers typically cover their floodplains with several or more feet of water, dropping layers of silt and mud. Ancient civilizations relied on this normal part of a river's cycle for replenishing and fertilizing their fields. Now that many floodplains are industrialized or populated by residential neighborhoods, the floods are no longer welcome and natural floods are regarded as disasters. On average, floods kill a couple of hundred people each year in the United States. Dikes and levees have been built around many rivers in attempts to keep the floodwaters out of towns. This exacerbates the flooding problem because it confines the river to a narrow channel, and the waters rise more quickly and cannot seep into the ground of the floodplain.

Streams are important geologic agents critical for other Earth systems. They carry most of the water from the land to the sea, they transport billions of tons of sediment to the beaches and oceans, and they erode and reshape the land's surface, forming deep valleys and floodplains and passing through mountains.

Streams and rivers are dynamic systems that constantly change their patterns, the amount of water (discharge) they carry, and the sediment transported by the system. Rivers can transport orders of magnitude more water and sediment during spring floods compared to low-flow times of winter or drought. Since rivers are dynamic systems, and the amount of water flowing through the channel changes, the channel responds by changing its size and shape to accommodate the extra flow. Five factors control how a river behaves: (1) width and depth of channel, measured in feet (m), (2) gradient, measured in feet per mile (m/km), (3) average velocity, measured in feet per second (m/sec), (4) discharge, measured in cubic feet per second (m^3/sec), and (5) load, measured as tons per cubic yard (metric tons/m^3). These factors continually interplay to determine the behavior of the river system. As one factor, such as discharge, changes, so do the others, expressed as:

$$Q = w \times d \times v$$

where Q represents discharge, w represents channel width, d represents channel depth, and v represents the velocity of the water in the channel.

All factors vary across stream, so they are expressed as averages. If one term changes then all or one of the others must change too. For example, with increased discharge, the river erodes and widens, and deepens its channel. The river may also respond by increasing the number of bends, known as meanders, and their curvature (measured as sinuosity), effectively creating more space for the water to flow

Kuskokwim River, just up from Bethel, Alaska, showing distributary channels, meanders, oxbow lakes, point bars, sand bars, and cut banks *(Paul Andrew Lawrence/Alamy)*

in and occupy by adding length to the river. The meanders can develop quickly during floods because the increased stream velocity adds more energy to the river system, and this can rapidly erode the cut banks enhancing the meanders.

The amount of sediment load available to the river is also independent of the river's discharge, so different types of river channels develop in response to different amounts of sediment load availability. If the sediment load is low, rivers tend to have simple channels, whereas braided stream and river channels develop where the sediment load is greater than the stream's capacity to carry that load. If a large amount of sediment is dumped into a river, it will respond by straightening, thus increasing the gradient and velocity and increasing its ability to remove the added sediment.

When rivers enter lakes or reservoirs along their path to the sea, the velocity of the water suddenly decreases. This causes the sediment load of the stream or river to be dropped as a delta on the lake bottom, and the river attempts to fill the entire lake with sediment in this manner. The river is effectively attempting to regain its gradient by filling the lake, then eroding the dam or ridge that created the lake in the first place. When the water of the river flows over the dam, it does so without its sediment load and therefore has greater power to erode the dam more effectively.

Rivers carry a variety of materials as they make their way to the sea. These materials range from minute dissolved particles and pollutants to giant boulders moved only during the most massive floods. The bed load consists of the coarse particles that move along or close to the bottom of the river bed. Particles move more slowly than the stream, by rolling or sliding. Saltation is the movement of a particle by short intermittent jumps caused by the current lifting the particles. Bed load typically constitutes between 5 and 50 percent of the total load carried by the river, with a greater proportion carried during high-discharge floods. The suspended load consists of the fine particles suspended in the river that make many rivers muddy. The particles of silt and clay move at the same velocity as the river. The suspended load generally accounts for 50–90 percent of the total load carried by the river. The dissolved load of a river consists of dissolved chemicals, such as bicarbonate, calcium, sulfate, chloride, sodium, magnesium, and potassium. The dissolved load tends to be high in rivers fed by groundwater. Rivers also carry pollutants, such as fertilizers and pesticides from agriculture and industrial chemicals, as dissolved load.

The range of sizes and amounts of material that a river can transport varies widely. The competence of a stream refers to the size of particles a river can transport under a given set of hydraulic conditions, measured in diameter of largest bed load. A river's capacity is the potential load it can carry, measured in the amount (volume) of sediment passing a given point in a set amount of time. The amount of material carried by rivers depends on a number of factors. Climate studies show erosion rates are greatest in climates between a true desert and grasslands. Topography affects river load, as rugged topography contributes more detritus, and some rocks are more erodable. Human activity, such as farming, deforestation, and urbanization, all strongly affect erosion rates and river transport. Deforestation and farming greatly increase erosion rates and supply more sediment to rivers, increasing their loads. Urbanization has complex effects, including decreased infiltration and decreased times between rainfall events and floods.

FLOODPLAINS

Floodplains are generally flat or low-lying areas that are adjacent and run parallel to river channels and are covered by water during flood stages of the river. The floodplain of a river is built by alluvium carried by the river and deposited in overbank environments, forming layers of silt, clay, and sand. Many narrow elongate channels filled by sands and gravels typically cut overbank deposits, marking places where the river formerly flowed and meandered away from during the course of river evolution. Sandy or gravelly levee deposits formed during flood stages of the river typically separate active and buried channels from floodplain deposits. These form because the velocity of floodwater decreases rapidly as it moves out of the channel, causing the current to drop heavy coarse-grained material near the river, forming a levee. Floodplains are also found around some lake basins that experience flood stages.

The increasing development and construction over floodplains creates potential and real hazards during floods. Floodplains are characterized by fertile soils and make excellent farmlands, which are nourished by yearly, decadal, and centurial floods, whereas buildings, towns, and cities have a much more difficult time dealing with periodic flooding.

FLUVIAL SYSTEMS AND CHANNEL TYPES

The term *fluvial* means "of the river," referring to different and diverse aspects of rivers. The term may be used to refer to the environment around rivers and streams, or more commonly, to refer to sediments deposited by a stream or river system.

Sediments deposited by rivers tend to become finer-grained and more rounded with increasing transport distance from the eroded source terrain, typically an uplifted mountain range. The sediments also tend to become more enriched in the stable chemical components, such as quartz and micas, and depleted in chemically vulnerable particles, such as feldspars.

Stream channels are rarely straight, and the velocity of flow changes in different places. Friction makes the flow slower on the bottom and sides of the channel, and the bends in the river make the zone of fastest flow swing from side to side. The character of channels changes in different settings because of differences in slope, discharge, and load. Straight channels are very rare, and those that do occur share many properties with curving streams. The thalweg is a line connecting the deepest parts of the channel. In straight segments, the thalweg typically meanders from side to side of the stream. In places where the thalweg is on one side of the channel, a bar may form on the other side. A bar (for example, a sand bar) is a deposit of alluvium in a stream

Most streams move through a series of bends known as meanders. Meanders are always migrating across the floodplain by the process of the deposition of the point bar deposits and the erosion of the bank on the opposite side of the stream with the fastest flow. The erosion typically occurs through slumping of the stream bank. Meanders typically migrate back and forth, and also down valley at a slow rate. If the downstream portion of a meander encounters a slowly erodable rock, the upstream part may catch up and cut off the meander. This forms an oxbow lake, which is an elongate and curved lake formed from the former stream channel.

A braided stream consists of two or more adjacent but interconnected channels separated by bars or an island. They form in many different settings, including mountain valleys, broad lowland valleys, and in front of glaciers. Braided streams tend to form where there are large variations in the volume of water flowing in the stream and a large amount of sediment is available to be transported during times of high flow. The channels typically branch, separate and reunite, forming a pattern similar to a complex braid. Braided streams have constantly shifting channels, which move as the bars are eroded and redeposited (during large fluctuations in discharge). Most braided streams have highly variable discharge in different seasons, and they carry more load than meandering streams. Braided streams form where the stream load exceeds the stream's capacity to carry the load.

The two or more adjacent but interconnected channels separated by bars or islands on braided streams constantly shift, moving as the bars are eroded and redeposited during large fluctuations in discharge. The highly variable discharge of braided streams enables them to carry more load than meandering streams.

River and stream channel deposits tend to be composed of sands and gravelly sands that exhibit large-scale three-dimensional ripples, shown in cross section as cross-bedding. These cross-bedded sands are common around the inner bends of channels and mark the former positions of point bars. They are often interbedded with planar-bedded sands marking flood stage deposits and gravelly sands deposited during higher flood stages. The tops of channel deposits are characterized by finer-grained sands with small scale ripples and mud drapes forming flaser-bedding, interbedded with muds, and grading up into overbank floodplain deposits. This upward-fining sequence is typical of fluvial deposits, especially those of meandering streams. In contrast, braided stream deposits show less order and are characteristically dominated by bed load material such as gravel and sand. They include imbricated gravels, gravels deposited in shallow scours, horizontally bedded sands, and gravels deposited in bars.

Fluvial channel deposits form a variety of geometric patterns on a more regional scale. Shoestring sands form a branched pattern of river channels enclosed in overbank shales and muds, formed by meandering and anastomosing river channels. Sheets and wedges of fluvial sediments form in front of uplifted mountain chains in foreland and rift basins, and they may pass basinward into deltaic or shallow marine sediments and mountainward into alluvial fan deposits. The type of tectonic setting for a basin can be deduced by changes or migration of different fluvial facies with stratigraphic height. Fluvial sediments are widely exploited for hydrocarbon deposits, and also are known for placer deposits of gold and other valuable minerals.

See also FLOOD; FLUVIAL.

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Russian geology The geology of Russia is dominated by the Archean Russian (East European) craton in the west, the Siberian craton in the north, and the large Altaid orogenic belt in the south. The Siberian craton is divided into the Aldan and Anabar shields. The Ural Mountains separate the Russian craton from the Siberian craton and the Altaids, and the Verkhoyansk-Kolyma block occupies northeasternmost Russia. Large parts of Siberia are covered by the Siberian flood basalts that formed during massive eruptions at the Permian-Triassic boundary and probably initiated the largest mass extinction known in Earth history. Siberia also stores vast amounts of the global carbon supply in the organic soils of the tundra and taiga.

RUSSIAN (EAST EUROPEAN) CRATON

The Russian or East European craton is well exposed in the Baltic states and in the Ukrainian shield, but it is mostly buried beneath late Precambrian to Phanerozoic cover in the Russian craton. The amalgamated East European craton, which formed the core of the Baltica block in the Proterozoic supercontinents of Rodinia and Gondwana, consisted of the Fennoscandian block (Baltic shield) in the northwest, the Volgo-Uralia block in the east, and the Sarmatia block in the south. The Baltic shield has a diverse Archean and Proterozoic crustal history including

Satellite image of Russia *(M-Sat Ltd/Photo Researchers, Inc.)*

several convergent margin accretionary events, while the core of Sarmatia appears to be older than the Baltic shield. Most of the Volgo-Uralia block is buried beneath thick younger cover, but deep drill holes have revealed Archean rocks at depth. Most of the East European craton is covered by a thick sequence of middle to late Proterozoic sedimentary cover that is 1.8 miles (3 km) thick, whereas most of the Baltic shield is exposed down to the Archean and late Proterozoic basement.

The Sarmatia block consists of the Ukrainian shield and the Voronezh uplift. The Ukrainian shield in the southern part of the East European craton consists of 3.8–3.2 billion-year-old rocks, exposed along the big bend of the Dneiper River. These rocks include five main granitoid-greenstone rich blocks, each separated by structurally complex belts containing banded-iron formations and other metasedimentary rocks. The Voronezh uplift north of the Ukrainian shield contains similar rocks and is separated from the Ukrainian shield by a younger rift, the Dneiper-Donets aulacogen.

The Ural Mountains, where the craton collided with the Siberian craton in the Late Paleozoic, mark the eastern margin of the East European craton. Phanerozoic sediments largely shed from the Alpine orogen bury the southern margin of the craton. The southwestern boundary of the East European craton is marked by the Trans-European suture zone, separating the craton from the Alpine and Variscan belts of western Europe. The Early Paleozoic Caledonian orogen truncates the northwestern margin of the craton.

SIBERIAN CRATON (ALDAN AND ANABAR SHIELDS)

The Siberian craton has Archean crust exposed in the Aldan and Anabar shields and in some of the Phanerozoic fold belts that surround the craton. Much of the craton is covered by thick platform sediments, and these are also underlain by Archean crust.

The Aldan shield contains a gneissic and migmatitic basement deformed into large oval gneiss domes. Granulite facies gneisses, known as the Aldan Supergroup, have yielded ages of 3.4 to 3.2 billion years old. Interspersed greenstone and schist belts known as the Subgan or Olondo Group have been dated to be about 3.0 billion years old. Both of these rock suites are cut by granitoid plutons that fall into two

Map showing the simplified geology and tectonics of Russia and surrounding areas, including the Russian (East European) craton, Siberian (Angara) craton, Urals, Altaids, and the Verkhoyansk Kolyma region.

age groups, 3.1–2.9 billion years and 2.6–2.5 billion years. The gneisses form domes that separate the belts of greenstones and schist, which are typically complexly deformed and show evidence of polyphase folding.

The Aldan Supergroup consists mostly of granulite facies gneiss with interleaved slivers of quartzites, marble, and calc-silicate rocks, reflecting that a deformed and highly metamorphosed shallow-water sedimentary type sequence is deformed along with the gneiss. The Aldan Supergroup can be divided into three main belts: the Aldan-Timpton block contains a lower assemblage of thick quartzite overlain by pyroxene-amphibole gneiss; this is unconformably overlain by hypersthene-tonalite gneiss, marble and cal-silicate rocks, with quartzite and mica-gneiss, and an upper sequence consisting of interlayered calcsilicates and graphitic gneiss.

The Subgan Group includes greenstone belts made predominantly of mafic to felsic metavolcanic rocks along with minor amounts of quartzites, banded-iron formation, and schist metamorphosed to greenschist to amphibolite facies. There are approximately 30 greenstone belts in the Aldan shield, most 15–100 miles (30–150 km) long, and 1.5–2 miles (2.5–4 km) wide. The structural geology of the greenstone belts is difficult to decipher, but it is clear that they are cut by many shear zones and have been through polyphase deformation. Their relationships with older gneisses are not well established.

The Aldan shield is cut by abundant granitoid plutons, including a 3.4–3.2 billion-year-old tonalite-charnockite series and a 2.6–2.5 billion-year-old group of biotite-rich granites and pegmatites.

The Anabar shield forms a plateau sitting 1,500 to 2,800 feet (500–900 m) above sea level. Geologically, the shield is divided into Archean granulites and anorthosites of the Anabar Complex and the early Proterozoic (1.9 billion years old) Lamyuka Complex. Most interpretations of the Lamyuka Complex suggest that it represents amphibolite-facies reworking of the Anabar Complex along 6–20 mile- (10–30 km-) wide and 120 mile- (200 km-) long belts of deep shearing and basement reactivation.

The Anabar Complex consists of high grade granulitic gneiss, schist, and migmatite that are strongly folded about north-northwest axes and deformed into broad domes. The gneisses have yielded ages of about 3.2 billion years old and show strong metamorphism at 2.7 billion years ago. Granodiorite plutons cut the older rocks and are elongate parallel to regional foliations and structural trends.

VERKHOYANSK-KOLYMA BLOCK

The Verkhoyansk Ranges of northeastern Siberia stretch about 600 miles (1,000 km) from the Lena to Aldan Rivers, rising to 8,150 feet (2,480 m). This mountain belt is located just to the west of the Eurasian-North American plate boundary and is known to host significant deposits of coal, silver, lead, and zinc. These remote ranges, which are covered in deep snow for most of the year, are famous for having the coldest temperatures on Earth for any inhabited region.

ALTAIDS

The Altaid orogenic belt stretches across southern Russia and several former Soviet Republics including Kazakhstan, Uzbekistan, Mongolia, and parts of China. This huge, poorly known mountain system forms about half of northern Asia and is bounded by the Siberian (Angara) and Russian cratons in the north and by the Alpine-Himalaya mountains, Tarim, and North China blocks in the south. The Urals bound the Altaids in the west, and the Baikal Mountains bound them in the east. There are two main schools of thought about the main tectonic events that led to the formation of the Altaid Mountains. The first suggests that a large number of different island arcs and small continents collided with each other in an oceanic setting and were then later accreted to continental land masses like the Siberian craton. The second group of models, championed by the Turkish geologist A. M. Celail Sengor, suggests that the Altaids are made of a collage of subduction-accretion materials that were added to a relatively few magmatic arcs, which then accreted to the Siberian and East European continents and were later disrupted and repeated by fault imbrication during large-scale strike-slip motions.

The Altaids grew around the Siberian craton from 600 to 144 million years ago. Consisting largely of continental crust that had already formed before the mountain ranges existed, they were brought together in convergent margin and collisional processes. Subduction-accretion complexes and magmatic arcs formed during the evolution of the Altaids, and blocks of continental crust of older ages were all stretched and thinned during the evolution of the mountain belt.

According to the model of Sengor, the Altaids are divided into 44 distinct tectonic units. Each of these different units may be composed of parts of cratons, magmatic arcs, passive margin fragments, and subduction/accretion complexes, now arranged into long curvilinear belts bounded by large strike-slip faults. Despite the complexity, three main rock assemblages of different rock types dominate the Altaids. These include

- turbidites and their low-grade metamorphic equivalents in flysch terranes
- pelagic sediments including chert, limestone, and shale, typically associated with the flysch
- mafic-ultramafic rock groups forming incomplete ophiolite suites

All of these rock groups are complexly deformed with multiple events of folding and faulting, and some belts are so deformed that they form tectonic mélanges. These three main rock assemblages are interspersed with terranes dominated by older, gneissic rocks, some with Mesozoic ages and others that are presumed to be Precambrian in age.

Tectonic Evolution of the Altaids

The tectonic evolution of the Altaids began in the Late Precambrian (Vendian) as a continental margin arc that had formed on the Baikalide-Uralide basement fringing the Angara (Siberian) and Russian (East European) cratons. This arc separated from the craton in the Early Cambrian, forming a long island arc known as the Kipchak arc. The arc was attached to continental crust on the Angara craton but lay offshore the East European craton. As the Russian and Angara cratons rifted and began rotating toward each other, the free end of the Kipchak arc collided with the Russian craton in an arc/continent collision event, followed by major strike-slip faulting. The arc was sliced into many pieces that then were stacked and repeated along the continental margins to form the Kazakhstan microcontinent. The tectonic collage was then caught between the colliding Russian and Angara cratons in the Late Carboniferous, causing the whole Altaid tectonic assemblage to be further flattened. By the Middle Jurassic all motion between the cratons had ceased.

South of the Angara craton (present reference frame), the Mongolian and Far East sections of the Altaids developed mostly within the realms of the Tuva-Mongolian basement, between Late Precambrian and Late Jurassic times. The evolution of this part of the Altaids was terminated by the final docking of a group of rocks called the "intermediate units" in Asia, including the Tarim basement and the North China craton. These blocks show a very complex history because Tethyan Ocean margin processes were affecting their southern margins, while their northern edges had not yet collided with the Altaids in the Jurassic. For some time they had subduction zones dipping beneath both their northern and southern margins, from the Altaids and from the Tethys Ocean.

URAL MOUNTAINS

The boundary between Europe and Asia is typically taken to be the Ural Mountains, a particularly straight mountain range that stretches 1,500 miles (2,400 km) from the Arctic tundra to the deserts north of the Caspian Sea. Naroda (6,212 feet; 1,894 m) and Telpos-Iz (meaning "nest of winds," 5,304 feet; 1,617 m) are the highest peaks, found in the barren rocky and tundra-covered northern parts of the range. Southern parts of the mountain range rise to 5,377 feet (1,639 m) at Yaman-Tau, in the Mugodzhar Hills. The southern parts of the range are densely forested, whereas the northern parts are barren and covered by tundra or bare rock.

The Ural River flows out of the southern Urals into the Caspian Sea, and the western side of the range is drained by the Kama and Belaya Rivers, tributaries that also feed into the Caspian Sea, providing more than 75 percent of the water that flows into this shallow, closed basin. The eastern side of the range is drained by the Ob-Irtysh drainage system that flows into the Ob Gulf on the Kara Sea.

The Urals are extremely rich in mineral resources, including iron ore in the south and large deposits of coal, copper, manganese, gold, aluminum, and potash. Ophiolitic rocks in the south are also rich in chromite and platinum, plus deposits of bauxite, zinc, lead, silver, and tungsten are mined. Basins on the western side of the Urals produce large amounts of oil, and regions to the south in the Caspian are yielding many new discoveries. The Urals are also very rich in rare minerals and gems, yielding many excellent samples of emeralds, beryl, and topaz.

The Urals form part of the Ural-Okhotsk mobile belt, a Late Proterozoic to Mesozoic orogen that bordered the Paleoasian Ocean. The Ural Mountains section of this orogen saw a history that began with Early Paleozoic, probably Cambrian rifting of Baikalian basement, and Late Ordovician spreading to form a back-arc or oceanic basin that was active until the mid-Carboniferous. Oceanic arcs grew in this basin, but by the Middle Devonian began colliding with the East European continent, forming flysch basins. The Kazakhstan microcontinent collided with the Laurussian continent in the Permian, forming a series of foredeep basins on the Russian and Pechora platforms. These foredeeps are filled with molasse and economically important Middle to Late Permian coal deposits as well as potassium salts.

The Urals show a tectonic zonation from the Permian flysch basins on the East European craton to the Permian molasse basins on the western slopes of the Urals, then into belts of allochthonous carbonate platform rocks derived from the East European craton and thrust to the west over the Permian foredeeps. These rocks are all involved in westward-vergent fold-thrust belt structures, including duplex structures, indicating westward tectonic transport in the Permian. The axial zone of the Urals includes a chain of anticlinoria bringing up Riphean rocks, whose eastern contact is known as the Main Uralian fault. This major fault zone brings oceanic and island arc rocks in large nappe and klippe structures, placing them over the passive margin sequence.

The eastern slope of the Urals consists of a number of Ordovician to Carboniferous oceanic and island arc synformal nappes, imbricated with slices of the Precambrian crystalline basement. It is uncertain if these Precambrian gneisses are part of the East European craton, part of the accreted Kazakhstan microcontinent, or an exotic terrane. The eastern slopes of the Urals are intruded by many Devonian-Permian granites.

SIBERIAN TRAPS

A large part of the central Siberian plateau northwest of Lake Baikal is covered by a thick series of mafic volcanic flows. They are more than half a mile thick (1 km) over an area of 210,000 square miles (543,900 km^2) but have been significantly eroded from an estimated volume of 1,240,000 cubic miles (5,168,545 km^3). This extraordinary sequence of lavas was erupted over a remarkably short period of less than 1 million years, 250 million years ago, at the Permian-Triassic boundary. Within the resolution of measurements, their age is coincident in time with the major Permian-Triassic extinction, implying a causal link. The Permian-Triassic boundary at 250 million years ago marks the greatest extinction in Earth history, when 90 percent of marine species and 70 percent of terrestrial vertebrates became extinct. It has been postulated that the rapid volcanism and degassing released enough sulfur dioxide to cause a rapid global cooling, inducing a short ice age with an associated rapid fall of sea level. Soon after the ice age took hold, the effects of the carbon dioxide took over and the atmosphere heated, resulting in a global warming. The rapidly fluctuating climate postulated to have been caused by the volcanic gases is thought to have killed off many organisms, which were simply unable to cope with the wildly fluctuating climate extremes.

SIBERIAN TAIGA FOREST AND GLOBAL CARBON SINK

The northern third of Asia, stretching from the Ural Mountains in the west to the Pacific coast into the east, is known as Siberia. The southern border of Siberia is generally taken to be the Kazakh steppes in the southwest, the Altai and Sayan Mountains in the south, and the Mongolian steppes in the southeast. This region occupies approximately 3,000,000 square miles (7,500,000 km^2). The western third of Siberia is occupied by the Siberian lowland, stretching from the Urals to the Yenisei River. This low marshy area is drained by the Ob River and its tributaries, and it hosts agriculture, industry, and most of Siberia's human population in the wooded steppe. Eastern Siberia stretches from the Yenisei River to a chain of mountains including the Yablonovy, Stanovoy, Verkhoyansk, Kolyma, and Cherskogo Ranges. The eastern half of Siberia is an upland plateau, drained by the Vitim and Aldan Rivers. The Lena runs along the eastern margin of the region, and Lake Baikal, the world's deepest lake, is located in the southeast. Northeasternmost Siberia hosts a smaller plain on the arctic coast between the Lena and Kolyma Rivers, in the Republic of Yakutia (Sakha).

Siberia shows a strong zonation of vegetation, including a zone of tundra that extends inland about 200 miles (300 km) from the coast, followed by the taiga forest, a mixed forest belt, and the southern steppes. Siberia's taiga forest accounts for about 20 percent of the world's total forested land, covering about two-thirds of the region. This region accounts for about half of the world's evergreen forest and buffers global warming by acting as a large sink for carbon that otherwise could be released into the atmosphere as carbon dioxide, a greenhouse gas. The forest and the rich soils derived from the decay of dead trees represents a very significant sink for global carbon. Much of the taiga forest is currently being logged at an alarming rate of loss of 12 million hectares per year. Much of this is being done by clear-cutting, where 90 percent of the timber is harvested, leading to increased erosion of the soil and runoff into streams. The effects of deforestation could be dramatic for global climate. With so much carbon stored in the taiga forest, both in the trees and in the peat and soils, any logging or development that releases this carbon to the atmosphere will increase global carbon dioxide levels, contributing to global warming. Acid rain and other pollution largely emitted from the coal, nickel, aluminum, and lead smelting plants in the west is causing additional loss of forest. Additionally, large tracts of forest are being torn up to explore for and extract oil, natural gas, iron ore, and diamonds.

See also ACCRETIONARY WEDGE; ARCHEAN; ASIAN GEOLOGY; CLIMATE CHANGE; CONVERGENT PLATE MARGIN PROCESSES; CRATON; DEFORMATION OF ROCKS; DIVERGENT PLATE MARGIN PROCESSES; EUROPEAN GEOLOGY; FLYSCH; GRANITE, GRANITE BATHOLITH; GREENSTONE BELTS; IGNEOUS ROCKS; LARGE IGNEOUS PROVINCES, FLOOD BASALT; MÉLANGE; PHANEROZOIC; PLATE TECTONICS; PROTEROZOIC; STRUCTURAL GEOLOGY; TRANSFORM PLATE MARGIN PROCESSES.

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Saturn Saturn is the sixth planet, residing between Jupiter and Uranus, orbiting at 9.54 astronomical units (888 million miles, or 1,430 million kilometers) from the Sun, twice the distance from the center of the solar system as Jupiter, and having an orbital period of 29.5 Earth years. The mass of Saturn is 95 times that of Earth, yet it rotates at more than twice the rate of Earth. The average density of this giant gaseous planet is only 0.7 grams/cm^3, less than water. The planet has a molecular hydrogen interior with a radius of 37,282 miles (60,000 km), a metallic hydrogen core with a radius of 18,641 miles (30,000 km), and a rocky/icy inner core with a radius of 9,320 miles (15,000 km).

The most striking features of Saturn are its many rings and moons, with the rings circling the planet along its equatorial plane and their appearance from Earth changing with the seasons because of the different tilt of the planet as it orbits the Sun. The rings are more than 124,275 miles (200,000 km) in diameter but are less than 30 feet (10 m) thick. They are composed of numerous small particles, most of which are ice between less than an inch (a few millimeters) and about 50 feet (a few tens of meters) in diameter. The breaks in the rings result from gravitational dynamics between the planet and its many moons.

Saturn has a yellowish-tan color produced largely by gaseous methane and ammonia, but the atmosphere consists of 92.4 percent molecular hydrogen, 7.4 percent helium, 0.2 percent methane, and 0.02 percent ammonia. These gases are stratified into three main layers, including a 62–124-mile- (100–200-km-) thick outer layer of ammonia, a 31–62-mile- (50–100-km-) thick layer of ammonium hydrosulfide ice, and a deeper 31–62-mile- (50–100-km-) thick layer of water ice. The atmosphere of Saturn is somewhat colder and thicker than that of Jupiter. Atmospheric winds on Saturn reach a maximum eastward-flowing velocity of 930 miles per hour (1,500 km/hr) at the equator and diminish with a few belts of high velocity toward the poles. Like Jupiter, Saturn has atmospheric bands related to these velocity variations, as well as turbulent storms that show as spots, and a few westward-flowing bands.

Many moons circle Saturn, including the large rocky Titan, possessing a thick nitrogen-argon-rich atmosphere that contains hydrocarbons including methane, similar to the basic building blocks of life on Earth. Other large to midsize moons include, in increasing distance from the planet, Mimas, Enceladus, Tethys, Dione, Rhea, and Iapetus. About a dozen other moons of significant size also circle the planet.

See also EARTH; JUPITER; MARS; MERCURY; NEPTUNE; SOLAR SYSTEM; URANUS; VENUS.

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Mosaic of Saturn taken by *Cassini,* October 2004: The mosaic is made from 126 images processed to show the planet in natural color. Saturn's equator is tilted relative to its orbit by 27 degrees, very similar to the 23-degree tilt of the Earth. As Saturn moves along its orbit, first one hemisphere, then the other is tilted toward the Sun. This cyclical change causes seasons on Saturn, just as the changing orientation of Earth's tilt causes seasons on our planet. Saturn's rings are incredibly thin, with a thickness of only about 30 feet (10 m). The rings are made of dusty water ice, in the form of boulder-sized and smaller chunks that gently collide with each other as they orbit around Saturn. Saturn's gravitational field constantly disrupts these ice chunks, keeping them spread out and preventing them from combining to form a moon. The rings have a slight pale reddish color due to the presence of organic material mixed with the water ice. Saturn is about 75,000 miles (120,000 km) across and is flattened at the poles because of its very rapid rotation. A day is only 10 hours long on Saturn. Strong winds account for the horizontal bands in the atmosphere of this giant gas planet. The delicate color variations in the clouds are due to smog in the upper atmosphere, produced when ultraviolet radiation from the Sun shines on methane gas. Deeper in the atmosphere, the visible clouds and gases merge gradually into hotter and denser gases. *(NASA Jet Propulsion Laboratory)*

sea-level rise Global sea levels are currently rising as a result of the melting of the Greenland and Antarctica ice sheets and thermal expansion of the world's ocean waters due to global warming. Earth is presently in an interglacial stage of an ice age. Sea levels have risen nearly 400 feet (122 m) since the last glacial maximum 20,000 years ago and about 6 inches (15 cm) in the past 100 years. The rate of sea-level rise seems to be accelerating, and may presently be as much as an inch (2.5 cm) every eight to 10 years. If all of the ice on both the Antarctic and Greenland ice sheets were to melt, global sea levels would rise by 230 feet (70 m), inundating most of the world's major cities and submerging large parts of the continents under shallow seas. The coastal regions of the world are densely populated and are experiencing rapid population growth. Approximately 100 million people presently live within three feet (1 m) above the present-day sea level. If sea level were to rise rapidly and significantly the world would experience an economic and social disaster of a magnitude not yet experienced by civilization. Many areas would become permanently flooded or subject to inundation by storms, beach erosion would be accelerated, and water tables would rise.

Sea level has risen and fallen by hundreds of feet many times in the billions of years represented by Earth history, and it is presently slowly rising at about one foot (0.3 m) per century, a rate that may be accelerating from the effects of global warming. The causes of sea-level rise and fall are complex, operate on vastly different time scales, and may affect local regions or the entire planet. These include growth and melting of glaciers, changes in the volume of the mid-ocean ridges, thermal expansion of water from global warming, and other complex interactions of the distribution of the continental landmass in mountains and plains during periods of faulting, mountain-building, and basin-forming activity. Deciphering the amount of sea-level rise depends critically on correct identification and separation of the local effects of the rising and sinking of the land, known as relative sea-level changes, from global changes in sea level, that are referred to as eustatic events.

Sometimes individual large earthquakes may displace the land surface vertically, resulting in subsidence or uplift of the land relative to the sea. One of the largest and best-documented cases of earthquake-induced subsidence resulted from the March 27, 1964, magnitude 9.2 earthquake in southern Alaska. This earthquake tilted a huge approximately 125,000-square-mile (200,000 square km) area of the Earth's crust. Significant changes in ground level were recorded along the coast for more than 600 miles (1,000 km), including uplifts of up to 36 feet (11 m), subsidence of up to 6.5 feet (2 m), and lateral shifts of 30 or more feet (several to tens of meters). Much of the area that subsided was along Cook Inlet, north to Anchorage and Valdez, and south to Kodiak Island. Towns that were built around docks prior to the earthquake were suddenly located below the high tide mark, and entire towns had to move to higher ground. Forests that subsided found their root systems suddenly inundated by salt water, leading to the death of the forests. Populated areas located at previously safe distances from the high-tide (and storm) line became prone to flooding and storm surges and had to be relocated.

The fastest changes in sea level are caused by instantaneous geologic catastrophes such as meteorite impacts into the ocean, but luckily these types of events do not happen often. Seasonal changes can blow or move water to greater heights on one side of a basin, move it to lower heights on another side, and cause water to expand and contract with changes in temperature, causing small changes in sea level. Climate changes can cause glaciers and ice caps to melt and reform, causing sea levels to rise and fall on time scales of hundreds to thousands of years. Longer-term climate variations related to variations in the orbit of the Earth around the Sun can lengthen the time scale of sea-level changes related to climate change to hundreds of thousands of years for individual cycles. Plate tectonics also influences sea-level changes, but on much longer time scales than climate variations. If the processes of seafloor spreading and submarine volcanism become accelerated in any geologic time period, the volume of material that makes up the mid-ocean ridge system will be larger, and this extra volume of elevated seafloor will displace an equal amount of seawater and raise sea levels. This process typically operates with time variations on the order of tens of millions of years. An even longer-term variation in sea levels is caused by the motions and collisions of continents in supercontinent cycles. When continents collide, large amounts of continental material are uplifted above sea level, effectively taking this material out of the oceans, making the ocean basins bigger, and lowering sea levels. When continents rift apart, the opposite happens—more material is added to the ocean basins, and sea levels rise on the continents. These slow tectonic variations can change sea levels on time scales of tens to hundreds of millions of years.

Rising sea levels cause the shoreline to move landward, whereas a fall in sea level causes the shoreline to move oceanward. With the present sea-level rise, coastal cliffs are eroding, barrier islands are migrating (or being submerged if they were heavily protected from erosion), beaches are moving landward, and the sea is flooding estuaries. At some point in the not too distant future, low-lying coastal cities will be flooded under several feet of water, and eventually the water could be hundreds of feet deep. Cities including New Orleans, New York, Washington, Houston, London, Shanghai, Tokyo, and Cairo will be inundated; the world's nations need to begin planning how to handle this inevitable geologic hazard and encroachment of the sea.

About 70 percent of the world's sandy beaches are being eroded. The reasons for this erosion include rising sea levels, increased storminess, a decrease in sediment transport to beaches from the damming of rivers, and perhaps shifts in global climate belts. Construction of sea walls to reduce erosion of coastal cliffs also causes a decreased supply of sand to replenish the beach, so also increases beach retreat. Pumping of groundwater from coastal aquifers also results in coastal erosion, because pumping causes the surface to subside, leading to a relative sea-level rise.

When sea level rises, beaches try to maintain their equilibrium profile and move each beach element landward. A sea-level rise of 1 inch (2.5 cm) is generally equated with a landward shift of beach elements of more than four feet (>1 m). Most sandy beaches worldwide are retreating landward at rates of 20 inches to 3 feet per year (0.5–1 m), consistent with sea-level rise of an inch (2.5 cm) every 10 years.

CAUSES OF CHANGING SEA LEVELS

The average position of the median sea level may appear to rise or fall with respect to the land surface to an observer on a shoreline, and this is called relative sea-level rise or fall. However, it is difficult for the observer on the local shoreline to know if the height of the water is changing, or if the height of the continent is rising or falling. In many places plate tectonics causes areas of the crust to rise slowly out of the sea or to sink gradually downward below sea level, while the water level is actually staying at the same height. The weight of glaciers or sedimentary deposits can also cause local shorelines to sink, or to rise if the weight is removed. Therefore geologists need a way to differentiate between local changes in relative sea level and true global sea-level changes. This is a difficult problem and is best done by obtaining accurate ages on the times of sea-level rise and fall and correlating these changes with other places around the world. This has been done through many years of study, and now there is a fairly well-established curve of global sea-level heights going back in geological time. Local or apparent changes in sea level are called apparent sea level, whereas global changes in the height of sea level are called eustatic sea-level changes.

Measuring global eustatic sea-level rise and fall is difficult because many factors influence the relative height of the sea along any coastline. These vertical motions of continents are called epeirogenic movements, and they may be related to plate tectonics, to rebound from being buried by glaciers, or to changes in the amount of heat added to the base of the continent by mantle convection. Continents may rise or sink vertically, causing apparent sea-level change, but these sea-level changes are relatively slow compared to changes induced by global warming and glacial melting. Slow, long-term sea-level changes can also be induced by changes in the amount of seafloor volcanism associated with seafloor spreading. At some times during Earth history seafloor spreading was particularly vigorous, and the increased volume of volcanoes and the mid-ocean ridge system caused global sea levels to rise.

INFLUENCE OF SHORT-TERM CLIMATE CHANGES ON SEA LEVEL

Minor changes in sea level of up to about a foot (30 cm) happen in many places in yearly seasonal cycles. Many of these are caused by changes in the wind patterns, as the Sun alternately heats different belts of the ocean, and the winds blow water from one side of the ocean to the other. When water is heated in the summer months it also expands slightly, accounting for sea-level changes of an inch (2.5 cm) or so. Thermal expansion associated with global warming may raise sea levels about 12 inches (30 cm) by the year 2050 and 20 inches (50 cm) by 2100. Seasonal development of regional high- and low-pressure systems that characterize some areas also change sea levels on short time scales. High pressure areas, such as the Bermuda high that often develops over the central Atlantic in the summer, lower local sea levels because the high atmospheric pressure (weight) pushes sea levels lower than in other times.

Steady winds and currents can amass water against a particular coastline, causing a local and temporary sea-level rise. Such a phenomenon is associated with the El Niño-Southern Oscillation (ENSO), causing sea levels to rise by 4–8 inches (10–20 cm) in the Australia-Asia region. When the warm water moves east in an ENSO event, sea levels may rise may 4–20 inches (10–50 cm) across much of the North and South American coastlines. The irregular El Niño event results from changes in atmospheric heating that then cause a warm current to move from the western Pacific to the eastern Pacific. This can raise sea levels off the coast of Peru (and sometimes as far as California) by up to 2 feet (60 cm), enough to cause enhanced erosion, landslides, and considerable damage to the coastal environment in South America. Other atmospheric phenomena can also change sea level by up to several feet (up to a few meters) locally, on short time scales. Changes in atmospheric pressure, salinity of seawaters, coastal upwelling, onshore winds, and storm surges all cause short-term fluctuations along segments of coastline. Global or local warming of waters can cause them to expand slightly, causing a local sea-level rise. The extraction and use of groundwater and its subsequent release into the sea might be causing sea-level rise of about 0.78 inch per year (1.3 mm/yr). Seasonal changes in river discharge can temporarily change sea levels along some coastlines, especially where winter cooling locks up large amounts of snow that melt in the spring.

Attempts to estimate eustatic sea-level changes must be able to average out the numerous local and tectonic effects to arrive at a globally meaningful estimate of sea-level change. Most coastlines seem to be dominated by local fluctuations that are larger in magnitude than any global sea-level rise. Recently, satellite radar technology has been employed to measure sea surface height precisely and to document annual changes in sea level. Radar altimetry is able to map sea-surface elevations to the subinch scale and to do this globally, providing an unprecedented level of understanding of sea-surface topography. Satellite techniques support the concept that global sea levels are rising at about 0.01 inch per year (0.025 cm/yr).

INFLUENCE OF LONG-TERM CLIMATE EFFECTS ON SEA LEVEL

Many changes in the Earth's climate that control relative sea level are caused by variations in the amount of incoming solar energy, which in turn are caused by systematic changes in the way the Earth orbits the Sun. These systematic changes in the amount of incoming solar radiation caused by variations in Earth's orbital parameters are known as Milankovitch cycles, after the Serbian mathematician Milutin Milankovitch, who first clearly described these cycles. These changes can affect many Earth systems, causing glaciations, global warming, dramatic sea-level

Tourists and residents wading in flooded St. Mark's Square in Venice, Italy, October 31, 2004 *(AP Images)*

changes, and changes in the patterns of climate and sedimentation.

Astronomical effects that influence the amount of incoming solar radiation include minor variations in the path of the Earth in its orbit around the Sun and the inclination or tilt of its axis, causing variations in the amount of solar energy reaching the top of the atmosphere. These variations are thought to be responsible for the advance and retreat of the Northern and Southern Hemisphere ice sheets in the past few million years and the associated huge sea-level changes. In the past 2 million years alone, the Earth has seen the ice sheets advance and retreat approximately 20 times. The climate record as deduced from ice-core records from Greenland and isotopic tracer studies from deep ocean, lake, and cave sediments suggests that the ice builds up gradually over periods of about 100,000 years, then retreats rapidly over a period of decades to a few thousand years. These patterns result from the cumulative effects of different astronomical phenomena.

Several movements are involved in changing the amount of incoming solar radiation. The Earth rotates around the Sun following an elliptical orbit. The shape of this elliptical orbit, called its eccentricity, changes cyclically with time over a period of 100,000 years, alternately bringing the Earth closer to and farther from the Sun in summer and winter. This 100,000-year cycle is about the same as the general pattern of glaciers advancing and retreating every 100,000 years in the past 2 million years, suggesting that this is the main cause of variations within the present-day ice age.

The Earth's axis is presently tilting by 23.5°N/S away from the orbital plane, and the tilt varies between 21.5°N/S and 24.5°N/S. The tilt changes by plus or minus 1.5°N/S from a tilt of 23°N/S every 41,000 years. When the tilt is greater, there is greater seasonal variation in temperature.

Wobble of the rotation axis describes a motion much like a top rapidly spinning and rotating with a wobbling motion, such that the direction of tilt toward or away from the Sun changes, even though the tilt amount stays the same. This wobbling phenomenon is known as precession of the equinoxes, and it has the effect of placing different hemispheres closest to the Sun in different seasons. Presently the precession of the equinoxes is such that the Earth is closest to the Sun during the Northern Hemisphere winter. This precession changes with a double cycle, with periodicities of 23,000 years and 19,000 years.

Because each of these astronomical factors acts on a different time scale, their effects are combined in a more complex cycle. These factors interact in a complicated way, known as Milankovitch cycles. Using the power of understanding these cycles, it is possible to make predictions of where the Earth's climate is heading, whether into a warming or cooling period, and whether sea levels will rise or fall, or if some regions may experience desertification, glaciation, floods, or droughts.

Present data shows that temperatures were about 3–5°F (2–3°C) cooler at the height of the glacial advances 12,000 years ago than they are today and that temperatures may warm an additional 3–4°C by the year 2100. If this warming occurs as predicted, then large amounts of the glacial ice on Antarctica and Greenland will melt, raising sea levels dramatically. Many scientists predict sea levels will rise at least a foot (0.3 m) by 2100, others predict more. The sea-level rise will likely continue past the year 2100, with at least 16 feet (5 m) over the next few centuries. When this happens, most of the world's large port cities will be partly to largely underwater and world civilizations will have needed to find ways to move huge populations to higher ground. There is a current debate about how much humans are contributing to global warming and the consequent sea-level rise. Most data suggest that human-induced warming is about or slightly less than 2°F (1°C) over the past 100 years, but that warming is superimposed on the longer-term cycles described above. What is not known is how these long-term natural cycles may change. Warming may continue, or the natural cycles may reverse, or other sudden catastrophic cooling events may occur, such as a volcanic eruption on the scale of Tambora in Indonesia in 1815 that lowered global temperatures by about 2°F (1°C).

SEA-LEVEL CHANGES CAUSED BY CHANGES IN WATER/ICE VOLUME

Global sea levels are currently rising, in part from thermal expansion of the seawater in a warmer climate, and partly as a result of the melting of the Greenland and Antarctic ice sheets. The Greenland and Antarctic ice sheets have some significant differences that cause them to respond differently to changes in air and water temperatures. The Antarctic ice sheet is about 10 times as large as the Greenland ice sheet, and since it sits on the South Pole, Antarctica dominates its own climate. The surrounding ocean is cold even during summer, and much of Antarctica is a cold desert with low precipitation rates and high evaporation potential. Most meltwater in Antarctica seeps into underlying snow and simply refreezes, with little running off into the sea. Antarctica hosts several large ice shelves fed by glaciers moving at rates of up to 1,000 feet (305 m) per year. Most ice loss in Antarctica is accomplished through calving and basal melting of the ice shelves, at rates of 10–15 inches (25–38 cm) per year.

In contrast, Greenland's climate is influenced by warm North Atlantic currents and by its proximity to other landmasses. Climate data measured from ice cores taken from the top of the Greenland ice cap show that temperatures have varied significantly in cycles of years to decades. Greenland also experiences significant summer melting, abundant snowfall, has few ice shelves, and its glaciers move quickly at rates of up to miles per year. These fast-moving glaciers are able to drain a large amount of ice from Greenland in relatively short amounts of time.

The Greenland ice sheet is thinning rapidly along its edges, losing an average of 15–20 feet (4.5–6 m) in the past decade. In addition, tidewater glaciers and the small ice shelves in Greenland are melting an order of magnitude faster than the Antarctic ice sheets, with rates of melting between 25–65 feet (7–20 m) per year, a rate that is apparently increasing. About half of the ice lost from Greenland is through surface melting that runs off into the sea. The other half of ice loss is through calving of outlet glaciers and melting along the tidewater glaciers and ice shelf bases.

These differences between the Greenland and Antarctic ice sheets lead them to play different roles in global sea level rise. Greenland contributes more to the rapid short-term fluctuations in sea level, responding to short-term changes in climate. In contrast, most of the world's water available for raising sea level is locked up in the slowly changing Antarctic ice sheet. Antarctica contributes more to the gradual, long-term sea-level rise.

PLATE TECTONICS, SUPERCONTINENT CYCLES, AND SEA LEVEL

Movement of the tectonic plates on Earth causes the semi-regular grouping of the planet's landmasses into a single or several large continents that remain stable for a long period of time, then disperse, and eventually come back together as new amalgamated landmasses with a different distribution. This cycle is known as the supercontinent cycle. At several times in Earth history, the continents have joined together to form one large supercontinent, with the last supercontinent Pangaea (meaning all land) breaking up approximately 160 million years ago. This process of supercontinent formation and dispersal and reamalgamation seems to be grossly cyclic, perhaps reflecting mantle convection patterns, but also influencing sea level, climate, and biological evolution.

The basic idea of the supercontinent cycle is that continents drift about on the surface until they all collide, stay together, and come to rest relative to the mantle. The continents are only half as efficient at conducting heat as oceans, so after the continents are joined together, heat accumulates at their base, causing doming and breakup of the continent. For small continents, heat can flow sideways and not heat up the base of the plate, but for large continents the lateral distance is too great for the heat to be transported sideways. The heat rising from within the Earth therefore breaks up the supercontinent after a heating period of several tens or hundreds of millions of years. The heat then flows away and is transferred to the ocean and atmosphere system, and continents move away until they come back together forming a new supercontinent.

The supercontinent cycle has many effects that greatly affect other Earth systems. First, the breakup of continents causes sudden bursts of heat release, associated with periods of increased, intense magmatism. It also explains some of the large-scale sea-level changes, episodes of rapid and widespread orogeny, episodes of glaciation, and many of the changes in life on Earth.

Sea level has changed by hundreds of meters above and below current levels at many times in Earth history. In fact, sea level is constantly changing in response to a number of different variables, many of them related to plate tectonics. The diversity of fauna on the globe is closely related to sea levels, with greater diversity during sea-level high stands, and lower diversity during sea-level lows. For instance, sea level was 1,970 feet (600 m) higher than now during the Ordovician Period, and the sea level high stand was associated with a biotic explosion. Sea levels reached a low stand at the end of the Permian Period, and this low was associated with a great mass extinction. Sea levels were high again in the Cretaceous.

SEA-LEVEL CHANGES RELATED TO CHANGES IN MID-OCEAN RIDGE VOLUME

Sea levels may change at different rates and amounts in response to changes in several other Earth systems. Local tectonic effects may mimic sea-level changes through regional subsidence or uplift, and these effects must be taken into account and filtered out when trying to deduce ancient, global (eustatic) sea-level changes. The global volume of the mid-ocean ridges can change dramatically, either by increasing the total length of ridges, or changing the rate of seafloor spreading. The total length of ridges typically increases during continental breakup, since continents are being rifted apart and some continental rifts can evolve into mid-ocean ridges. Additionally, if seafloor spreading rates are increased, the amount of young, topographically elevated ridges is increased relative to the slower, older topographically lower ridges that occupy a smaller volume. If the volume of the ridges increases by either mechanism, then a volume of water equal to the increased ridge volume is displaced and sea level rises, inundating the continents. Changes in ridge volume are able to change sea levels positively or negatively by about 985 feet (300 m) from present values, at rates of about 0.4 inch (1 cm) every 1,000 years.

SEA-LEVEL CHANGES RELATED TO CHANGES IN CONTINENTAL AREA

Continent-continent collisions can lower sea levels by reducing the area of the continents. When continents collide, mountains and plateaus are uplifted, and the amount of material that is taken from below sea level to higher elevations no longer displaces seawater, causing sea levels to drop. The ongoing India-Asia collision has caused sea levels to drop by 33 feet (10 m).

Other things, such as mid-plate volcanism, can also change sea levels. The Hawaiian Islands are hot-spot style mid-plate volcanoes that have been erupted onto the seafloor, displacing an amount of water equal to their volume. Although this effect is not large at present, at some periods in Earth history there were many more hot spots (such as in the Cretaceous Period), and the effect may have been larger.

The effects of the supercontinent cycle on sea level may be summarized as follows: Continent assembly favors regression, whereas continental fragmentation and dispersal favors transgression.

SUMMARY

Sea level is rising presently at a rate of one foot (0.3 m) per century, although this rate seems to be accelerating. This rising sea level will obviously change the coastline dramatically—a one-foot (0.3-m) rise in sea level along a gentle coastal plain can be equated with a 1,000-foot (300-m) landward migration of the shoreline. The world will look significantly different when sea levels rise significantly. Many of the world's low-lying cities like New York, New Orleans, London, Cairo, Tokyo, and most other cities in the world may look like Venice in a hundred or several hundred years. The world's rich farmlands on coastal plains, like the East Coast of the United States, northern Europe, Bangladesh and much of China will be covered by shallow seas. If sea levels rise more significantly, as they have in the past, then vast parts of the interior plains of North America will be covered by inland seas, and much of the world's climate and vegetation zones will be shifted to different latitudes.

Governments must begin to plan for how to deal with rising sea levels, yet very little has been done so far. It is time that groups of scientists and government planners begin to meet to first understand the magnitude of the problem, then to study and recommend which tactics to initiate to mitigate the effects of rising sea levels.

See also El Niño and the Southern Oscillation (ENSO); glacier, glacial systems; plate tectonics.

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seawater The oceans cover more than 70 percent or the Earth's surface and extend to an average depth of a couple of miles (several kilometers). As part of the hydrologic cycle, each year approximately 1.27 × 10^{16} cubic feet (3.6 × 10^{14} m^3) of water evaporate from the oceans with about 90 percent of this returning to the oceans as rainfall. The remaining 10 percent falls as precipitation on the continents, where it forms freshwater lakes and streams and seeps into the groundwater system for temporary storage before eventually returning to the sea. During its passage over and in the land, the water erodes huge quantities of rock, soil, and sediment, and dissolves chemical elements such as salts from the continents, carrying these and other sediments as dissolved, suspended, and bed load to the oceans. Water transports more than 50 million tons of continental material into the oceans each year. Most of the suspended and bed load material is deposited as sedimentary layers near passive margins, but the dissolved salts and ions derived from the continents play a major role in determining seawater chemistry, as listed in the table "Composition of Typical Seawater." The most abundant dissolved salts are chloride and sodium, which together with sulfate, magnesium, calcium, potassium, bicarbonate, bromide, borate, strontium, and fluoride form more than 99.99 percent of the total material dissolved in seawater.

In addition to the elements listed in the table "Composition of Typical Seawater," a number of additional minor and trace elements dissolved in seawater are important for the life cycle of many organisms. For instance, nitrogen, phosphorus, silicon, zinc, iron, and copper play important roles in the growth of tests and other parts of some marine organisms. Seawater also contains dissolved gases, including nitrogen, oxygen, and carbon dioxide. The amount of oxygen dissolved in the surface layers of

COMPOSITION OF TYPICAL SEAWATER

Name	Symbol	Concentration in Parts per Thousand	Percentage of Dissolved Material
Chloride	Cl^-	18.980	55.05
Sodium	Na^+	10.556	30.61
Sulfate	SO_4^{2-}	2.649	7.68
Magnesium	Mg^{2+}	1.272	3.69
Calcium	Ca^{2+}	0.400	1.16
Potassium	K^+	0.380	1.10
Bicarbonate	HCO^{3-}	0.140	0.41
Bromide	Br^-	0.065	0.19
Borate	H_3BO^{3-}	0.026	0.07
Strontium	Sr^{2+}	0.008	0.03
Fluoride	F^-	0.001	0.00
Total		**34.477**	**99.99**

seawater is about 34 percent of the total dissolved gases, significantly higher than the 21 percent of the total atmospheric gases. Marine organisms generate this oxygen through photosynthesis. Some of it exchanges with the atmosphere across the air-water interface, and some sinks and is used by deep aerobic organisms. The amount of carbon dioxide dissolved in seawater is about 50 times greater than its concentration in the atmosphere. CO_2 plays an important role in buffering the acidity and alkalinity of seawater where, through a series of chemical reactions, it keeps the pH of seawater between 7.5 and 8.5. Marine organisms make carbonate shells out of the dissolved CO_2, and some is incorporated into marine sediments where it is effectively isolated from the atmosphere. The total amount of CO_2 stored in the ocean is very large, and as a greenhouse gas, if it were to be released to the atmosphere, it would have a profound effect on global climate.

The salinity and temperature of seawater are important in controlling mixing between surface and deep water and in determining ocean currents. Temperature is controlled largely by latitude, whereas river input, evaporation from restricted basins, and other factors determine the total dissolved salt concentration. Density differences caused by temperature and salinity variations induce ocean currents and thermohaline circulation, distributing heat and nutrients around the globe.

See also GEOCHEMICAL CYCLES; HYDROSPHERE; OCEAN BASIN; OCEAN CURRENTS; OCEANOGRAPHY; THERMOHALINE CIRCULATION.

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Sedgwick, Adam (1785–1873) British *Geologist* One of the founders of geology as a science, Adam Sedgwick was born on March 22, 1785, in Yorkshire, England. He was the third of seven children of the Anglican vicar of the town of Dent, and he spent a happy childhood with many hours exploring the countryside collecting fossils and rocks. Sedgwick attended the Sedberg School in Yorkshire, then he was admitted to Trinity College at Cambridge University on a special scholarship, obtaining his bachelor of arts in natural sciences in 1808. The college made him a fellow in 1810, when he was charged with supervising six students, which he noted seriously held him back in his own studies.

In 1818 Sedgwick was appointed the Woodwardian professor of geology at Cambridge, which had been endowed by natural historian John Woodward in the early 1700s. Until this time, Sedgwick had not had any formal studies in geology, and is credited with saying, "Hitherto I have never turned a stone; henceforth I will leave no stone unturned," upon his appointment to the post. While in this post Sedgwick taught himself geology and paleontology and paid great attention to expanding the geological collections of Cambridge University, while gaining experience by doing field work throughout the British Isles. Sedgwick became a very popular lecturer and went against tradition of the times by allowing women to attend his courses. In 1829 he was elected president of the Geological Society of London, and in 1845 he became a vice-master of Trinity College. Sedgwick's health began faltering in the 1850s, and he stopped giving lectures due to his health in 1871.

Adam Sedgwick was exploring the field of geology in England at a time when the science was in its infancy. He met and worked with gentleman geologist Roderick Murchison, and the two jointly presented their research on some fossiliferous rocks of Devonshire, England. The distinctive fossil assemblage in these rocks led Sedgwick and Murchison to propose a new division of geologic time for these rocks—the Devonian period. In the early 1830s the two began working on the folded and faulted rocks of Wales. Murchison worked on the fossil assemblages and determined that they appeared more primitive (containing fewer fish) than the rocks of Devonshire, so he assigned these rocks to an older period, naming it the Silurian after the Silures, a Celtic tribe who lived in the Welsh borderlands in Roman times. Sedgwick then suggested that even older rocks existed in central Wales, and he named these the Cambrian, after Cambria, the Latin name for Wales. Sedgwick and Murchison then presented their descriptions of the rocks and stratigraphic divisions of England and Wales in a famous paper called "On the Silurian and Cambrian Systems, Exhibiting the Order in Which the Older Sedimentary Strata Succeed Each Other in England and Wales." The paper became famous as it offered the first division of lower Paleozoic time. During these studies Sedgwick became the first geologist to clearly distinguish between the structures of jointing, slaty cleavage, and stratification.

There was some overlap between the upper part of the Cambrian as proposed by Sedgwick and the lower part of the Silurian as proposed by Murchison. This led to a major dispute between Sedgwick and Murchison, with both claiming they were correct. At stake was the honor of being the first person to describe the rocks that seemingly contained the earliest record of life on Earth since, at that time, the oldest fossils known were Cambrian. Murchison claimed that Sedgwick's Cambrian rocks were not sufficiently different from his Silurian rocks to warrant a further division of geologic time. The debate was resolved in 1879 when British geologist Charles Lapworth proposed a new division of geologic time between the Cambrian and Silurian, which he called the Ordovician after a Celtic tribe in Wales. The Ordovician included both the disputed Upper Cambrian and Lower Silurian strata.

During some of his field work in Wales, Sedgwick took a student from Cambridge along as a field assistant—the young Charles Darwin. Darwin was in Sedgwick's geology lecture course and wanted more experience so took the employment from Sedgwick. This experience proved invaluable, as during Darwin's famous voyage on the HMS *Beagle* (1831–36) Darwin sent many rock samples and descriptions of South America back to Sedgwick, who read and helped interpret the work. Sedgwick also highly recommended Darwin's work to the Geological Society of London, improving the career and reputation of his former student and then colleague. However, later Sedgwick did not approve of Darwin's theory of evolution, writing in a letter to Darwin after reading his *On the Origin of Species* that "other parts I read with absolute sorrow; because I think them utterly false and grievously mischievous—You have deserted—after a start in that tram-road of all solid physical truth—the true method of induction."

Sedgwick was a geologic catastrophist, believing most Earth history events could be explained by a series of major catastrophes, much as described by the French geologist Georges Cuvier (1769–1832), and opposed to the gradualistic models of Sir Charles Lyell. Sedgwick's main opposition to Darwin's model for evolution was its apparent lack of any involvement of a divine being or creation. Although Sedgwick believed in the great lengths of geological time, he thought that there was a god in the evolution of life and the Earth, arguing with Darwin that "there is a moral or metaphysical part of nature as well as a physical."

See also CAMBRIAN; CARBONIFEROUS; DARWIN, CHARLES; LIFE'S ORIGINS AND EARLY EVOLUTION; LYELL, SIR CHARLES; ORDOVICIAN; SORBY, HENRY CLIFTON.

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sedimentary rock, sedimentation

Sedimentary rocks are rocks that have consolidated from accumulations of loose sediment produced by physical, chemical, or biological processes. Common physical processes involved in the formation of sediments include the breaking, transportation of fragments, and accumulation of older rocks; chemical processes include the precipitation of minerals by chemical processes or evaporation of water; common biological processes include the accumulation of organic remains.

Soils and other products of weathering of rocks are continuously being removed from their sources and deposited elsewhere as sediments. This process can be observed as gravel in streambeds, on alluvial fans, and in wind-blown deposits. When these sediments are cemented together, commonly by minerals deposited from water percolating through the ground, they become sedimentary rocks. Other types of sedimentary rocks are purely chemical in origin, and were formed by the precipitation of minerals from an aqueous solution.

Clastic sediments (also detritus) are the accumulated particles of broken rocks, some with the remains of dead organisms. The word clastic is from the Greek word *klastos,* meaning broken. Most clastic particles have undergone various amounts of chemical change, and some have a continuous gradation in size from huge boulders to submicroscopic particles. Size is the main basis for classifying clastic sediments and sedimentary rocks. The textures of the sedimentary rocks or individual sedimentary particles act as additional criteria for the classification of sedimentary rocks.

Clastic sediments can be transported by wind, water, ice, or gravity, and each method of transport leaves specific clues as to how it was transported and deposited. For instance, deposits from sediments transported by gravity in a landslide will consist of a poorly sorted mixture including everything that was in the path, whereas sediment transported by wind will have a very uniform grain size and typically forms large dunes. Clastic sediments are deposited when the transporting agent can no longer carry them. For instance, if the wind stops, the dust and sand will fall out, whereas sediments transported by streams are deposited when the river velocity slows down. This happens either where the stream enters a lake or the ocean or when a flood stage lowers and the stream returns to a normal velocity and clears up. Geologists can look at old rocks and tell how fast the water was flowing during deposition and can also use clues such as the types of fossils or the arrangement of the individual particles to decipher the ancient environment.

Chemical sediment is sediment formed when minerals precipitate from solution. They may result from biochemical activities of plants and animals that live in the water, or they may form from inorganic reactions in the water, induced by things such as hot springs or simply the evaporation of seawater. This produces a variety of salts, including ordinary table salt. Chemical sedimentary rocks are classified according to their main chemical component, with common types including limestone (made of predominantly calcite), dolostone (consisting of more than 50 percent dolomite), rock salt (composed of NaCl), and chert (whose major component is SiO_2).

Evaporite sediments include salts precipitated from aqueous solutions, typically associated with the evaporation of desert lake basins known as playas, or the evaporation of ocean waters trapped in restricted marine basins associated with tectonic movements and sea level changes. They are also associated with sabkha environments along some coastlines such as along the southern side of the Persian (Arabian) Gulf, where seawater is drawn inland by capillary action and evaporates, leaving salt deposits on the surface.

Evaporites are typically associated with continental breakup and the initial stages of the formation of ocean basins. For instance, the opening of the south Atlantic Ocean about 110 million years ago is associated with the formation of up to 3,280 feet (1,000 m) of salts north of the Walvus-Rio Grande Ridge. This ridge probably acted as a barrier that episodically (during short sea-level rises) let seawater spill into the opening Atlantic Ocean, where it evaporated in the narrow rift basin. A column of ocean water about 18.5 miles (30 km) thick would be necessary to form the salt deposits in the south Atlantic, suggesting that water spilled over the ridge many times during the opening of the basin. The evaporate-forming stage in the opening of the Atlantic probably lasted about 3 million years, perhaps involving as many as 350 individual spills of seawater into the restricted basin. Salts that form during the opening of ocean basins are economically important because when they get buried under thick piles of passive continental margin sediments, the salts typically become mobilized and intrude overlying sediments as salt diapirs, forming salt domes and other oil traps exploited by the petroleum industry.

Salts can also form during ocean closure, with examples known from the Messinian (Late Miocene) of the Mediterranean region. In this case thick deposits of salt with concentric compositional zones reflect progressive evaporation of shrinking basins, when water spilled out of the Black Sea and Atlantic into a restricted Mediterranean basin. So-called closing salts are also known from the Hercenian orogen north of the Caspian Sea and in the European Permian Zechstein basin in the foreland of the collision.

As seawater evaporates, a progressive sequence of different salts forms from the concentrated brines. Typically, anhydrite ($CaSO_4$) is followed by halite (NaCl), which forms the bulk of the salt deposits. A variety of other salts can form depending on the environment, composition of the water being evaporated, when new water is added to the brine solution, and whether or not it partly dissolves existing salts.

Most sedimentary rocks display a variety of internal and surface markings known as sedimentary structures that can be used to interpret the conditions of formation. Stratification results from a layered arrangement of particles in a sediment or sedimentary rock that accumulated at the surface of the Earth. The layers are visible and distinct from adjacent layers because of differences (such as size, shape, or composition) in the particles between successive layers and because of differences in the way the particles are arranged between different layers. Bedding is the layered arrangement of strata in a body of rock. Parallel strata are sedimentary layers in which individual layers lie parallel to one another. The presence of parallel strata usually means that the sediments were deposited underwater, such as in lakes or in the deep sea. Some sediments with parallel layers have a regular alternation between two or more types of layers, indicating a cycle in the depositional environment. These can be daily, yearly, or some other rhythm influenced by solar cycles. One unusual type of layered rock is a varve, which is a lake sediment that forms a repeating cycle of coarse-grained sediments with spring tides, and fine clay with winter conditions, when the suspended sediments gradually settle out of the water column. Cross strata are layers that are inclined with respect to larger layers in which they occur. Most cross-laminated deposits are sandy or coarser, and they form as ripples that move along the surface. The direction of inclination of the cross strata is the direction that the water formerly flowed.

Sorting is a sedimentary characteristic that refers to the distribution of grain sizes within a sediment or sedimentary rock. Sediments deposited by wind are typically well sorted, but those deposited by water may show a range of sorting. A bed is called uniform if its layers contain grains with the same size throughout. A gradual transition from coarse- to fine-grained, or fine- to coarse-grained, is known as a graded bed. Graded beds typically reflect a change in current velocity during deposition. Nonsorted layers represent a mixture of different grain sizes, without any apparent order. These are common in rock falls, avalanche deposits, landslides, and from some glaciers. *Rounding* is a textural term that describes the relative shape or roundness of grains. When sediments first break off from their source area, they tend to be angular and reflect the shape of joints or internal

Cross-bedded Navajo sandstone from the Jurassic period in Zion National Park, Utah *(François Gohier/Photo Researchers, Inc.)*

mineral forms. With progressive transportation by wind or water, abrasion tends to smooth the grains and make them rounded. The greater the transport distance, in general, the greater the rounding.

Surface features on sedimentary layers also yield clues about the depositional environment. Like ripple marks or footprints on the beach, many features preserved on the surface of strata offer clues about the origin of sedimentary rocks and the environments in which they formed. Ripple marks show the direction of ancient currents, whereas tool marks record places where an object was dragged by a current across a surface. Turbulent eddies in a current produce grooves in the underlying sediment called flute marks, by scouring out small pockets on the paleosurface. Mud cracks reveal that the surface was wet, then desiccated by subaerial exposure. Other types of surface marks include footprints and animal tracks in shallow water environments, and raindrop impressions in subaerial settings.

Fossils are remains of animals and plants preserved in the rock that can also reveal clues about past environments. For instance, deep marine fossils are not found in lake environments, and dinosaur footprints are not found in deep marine environments.

See also ARABIAN GEOLOGY; BASIN, SEDIMENTARY BASIN; CONTINENTAL MARGIN; HISTORICAL GEOLOGY; OCEAN BASIN; PETROLEUM GEOLOGY; PETTIJOHN, FRANCIS JOHN; SEQUENCE STRATIGRAPHY; STRATIGRAPHY, STRATIFICATION, CYCLOTHEM.

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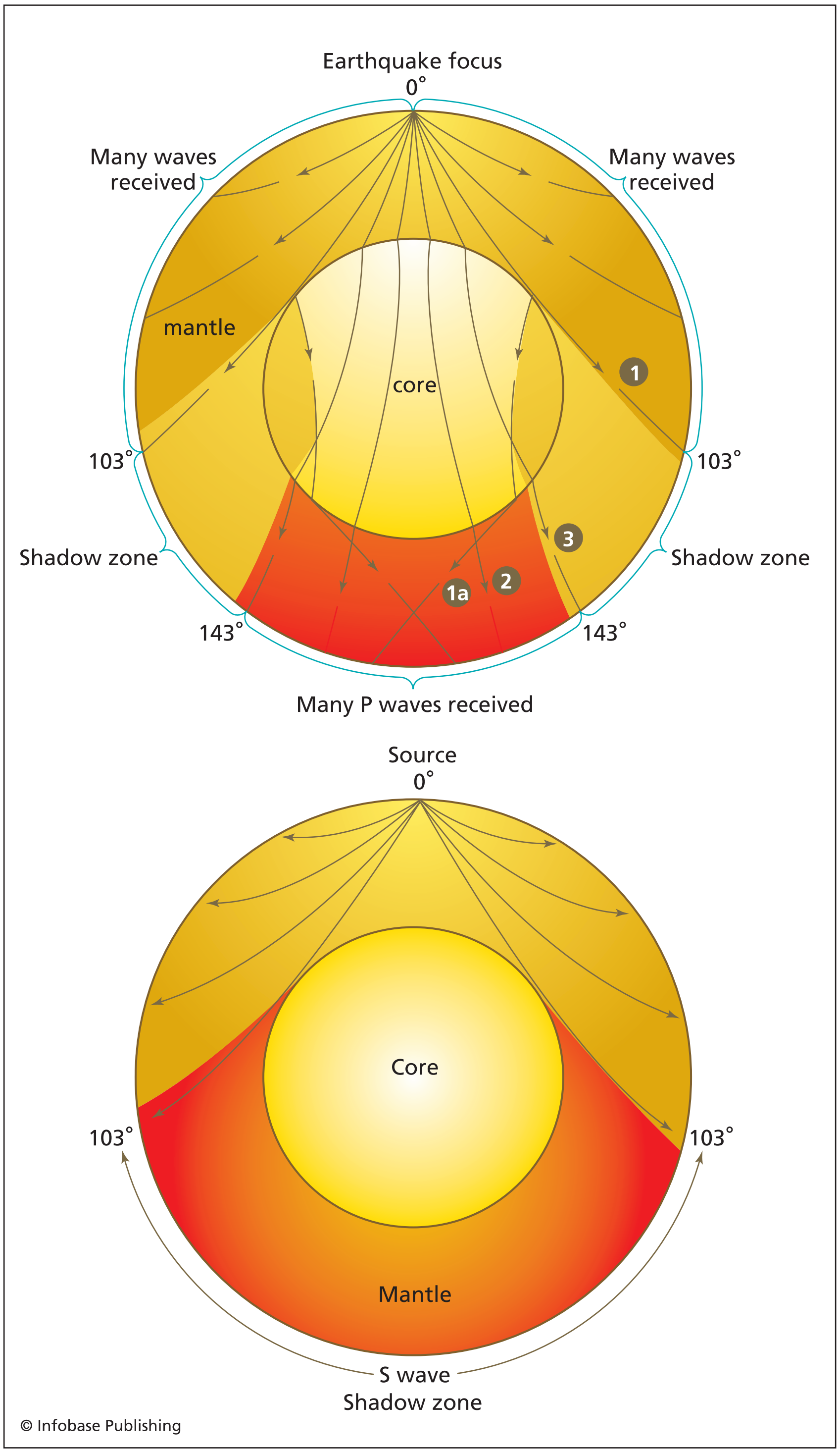
seismology The study of the propagation of seismic waves through the Earth, including analysis of earthquake sources, mechanisms, and the determination of the structure of the Earth through variations in the properties of seismic waves is called seismology.

Determination of the structure of the deep parts of the Earth can be achieved only by remote geophysical methods such as seismology. Seismographs are stationed all over the world, and studying the propagation of seismic waves from natural and artificial source earthquake and seismic events allows for the calculation of changes in the properties of the Earth in different places. If the Earth had a uniform composition, seismic wave velocity would increase smoothly with depth, because increased density is equated with higher seismic velocities. However, by plotting the observed arrival time of seismic waves, seismologists have found that the velocity does not increase steadily with depth but that several dramatic changes occur at discrete boundaries and in transition zones deep within the Earth.

One can calculate the positions and changes across these zones by noting several different properties of seismic waves. Some are reflected off interfaces, just like light is reflected off surfaces, and other waves are refracted, changing the velocity and path of the rays. These reflection and refraction events happen at specific sites in the Earth, and the positions of the boundaries are calculated using wave velocities. The core-mantle boundary at 1,802 miles (2,900 km) depth in the Earth strongly influences both P and S waves. It refracts P-waves, causing a P-wave shadow and, because liquids cannot transmit S waves, none get through, causing a huge S-wave shadow. These



Cross sections of the Earth showing shadow zones that develop in bands around the planet due to refraction of P and S waves at internal boundaries

contrasting properties of P and S waves can be used to accurately map the position of the core-mantle boundary.

Variations in the propagation of seismic waves illustrate several other main properties of the deep Earth. Velocity gradually increases with depth to about 62 miles (100 km), where the velocity drops slightly between 62 and 124 miles (100–200 km) depth, in a region known as the low velocity zone. The reason for this drop in velocity is thought to be small amounts of partial melt in the rock, corresponding to the asthenosphere, the weak sphere on which the plates move, lubricated by partial melts.

Another seismic discontinuity exists at 248.5 miles (400 km) depth, where velocity increases sharply due to a rearrangement of the atoms within olivine in a polymorphic transition into spinel structure, corresponding to an approximate 10 percent increase in density.

A major seismic discontinuity at 416 miles (670 km) could be either another polymorphic transition or a compositional change, the topic of many current investigations. Some models suggest that this boundary separates two fundamentally different types of mantle, circulating in different convection cells, whereas other models suggest that there is more interaction between rocks above and below this discontinuity.

The core-mantle boundary is one of the most fundamental on the planet, with a huge density contrast from 5.5 g/cm^3 above, to 10–11 g/cm^3 below, a contrast greater than that between rocks and air on the surface of the Earth. The outer core is made dominantly of molten iron. An additional discontinuity occurs inside the core at the boundary between the liquid outer core and the solid, iron-nickel inner core.

The properties of seismic waves can also be used to understand the structure of the Earth's crust. Andrija Mohorovičić (a Yugoslavian seismologist) noticed slow and fast arrivals from nearby earthquake source events. He proposed that some seismic waves traveled through the crust, some along the surface, and that some were reflected off a deep seismic discontinuity between seismically slow and fast material at about 18.6

PREDICTING FUTURE EARTHQUAKES IN THE WESTERN UNITED STATES

The Earth is a dynamic planet composed of different internal layers that are in constant motion, driven by a vast heat engine deep in the planet's interior. The cool surface layer is broken into dozens of rigid tectonic plates that move around on the surface at rates of up to a few inches (~5 cm) per year, driven by forces from the internal heat and motion in the partly molten layers within the planet. Most destructive earthquakes are associated with motions of continents and ocean floor rocks that are part of these rigid tectonic plates riding on moving parts of the Earth's interior. Plate tectonics is a model that describes the process related to the slow motions of more than a dozen of these rigid plates of solid rock riding around on the surface of the Earth. The plates ride on a deeper layer of partially molten material that is found at depths starting at 60–200 miles (100–320 km) beneath the surface of the continents, and 1–100 (1–160 km) miles beneath the oceans. The motions of these plates involve grinding, sticking, and sliding where the different plates are in contact and moving in different directions, causing earthquakes when sudden sliding motions occur along faults. These earthquakes release tremendous amounts of energy, raising mountains and, unfortunately, sometimes causing enormous destruction.

For many years there has been much speculation about the effects of the anticipated magnitude 7–9 earthquake, or the "big one," in southern California. This speculation and fear is not unfounded. The unrepentant forces of plate tectonics continue to slide the Pacific plate northward relative to North America along the San Andreas Fault, and the stick-slip type of behavior that characterizes segments of this fault system generates many earthquakes. Several segments of the fault have seismic gaps, where the tectonic stresses may be particularly built up. One of these gaps released its stress during the Loma Prieta earthquake of 1989, but other gaps remain, including the large area generally east of Los Angeles. Some models predict that the seismic energy may be released in this area by a series of moderate earthquakes (magnitude 7), but other, more sinister predictions also remain plausible. The last major rupture along the southern California segment was in 1680, and the event before that occurred between 1330–1480. Studies of prehistoric earthquakes in this region show that major, catastrophic events recur roughly every 350 years. In this scenario, the next major event could be expected sometime around the year 2030, with a large margin of error, and the magnitude could reach or exceed 8 on the Richter scale. Such an event would be truly devastating to urban areas in southern California, and would result in tremendous loss of life and property. Residents should prepare, having emergency plans and supplies ready, and understand the different risks in their specific locations.

What Can the Pacific Northwest Expect?

Only 15 years ago many people in the Seattle area thought they were far enough away from active faults to not have to worry about earthquakes. Scientists thought the Cascadia subduction zone beneath the Pacific Northwest was aseismic since it had not produced any earthquakes in at least a couple of hundred years. Then, on February 28, 2001, a magnitude 6.8 earthquake lasting 45 seconds and injuring 250 people sent Seattle a rude wake-up call. Since then, scientists and residents have come to realize that the Cascadia subduction zone forms a potential threat for earthquakes, even for great earthquakes (magnitudes greater than 8) similar in magnitude to the December 26, 2004, Indonesian earthquake. In addition to the active seismicity, this realization comes in part from studies that have identified paleoearthquakes and tsunami deposits from local earthquakes.

The U.S. Geological Survey has identified three main potential sources for Pacific Northwest earthquakes, including deep ruptures that originate along the subduction zone thrust and have in the past generated magnitude 6.5–7.1 earthquakes in this area. The second potential source is within the upper plate over the subduction zone, where events greater than magnitude 7 have occurred in the past (1872, 1918, and 1946). The third source is potentially the most destructive, including the shallow segment of the subduction zone where ruptures can be large and include significant surface movements, generating tsunami. The most recent giant (~ magnitude 9) shallow subduction zone quake in the area was in 1700, where the earthquake triggered a huge tsunami that damaged parts of Japan and left deposits around the Pacific Northwest area. It is estimated that events of this size occur every 400–600 years in the Cascadia subduction zone, and the clock is ticking.

A magnitude 9 earthquake in the Cascadia subduction zone would be devastating to the Seattle-Tacoma-Aberdeen-Bellingham area, including at least several minutes of shaking (for comparison, the Sumatra earthquake had up to 10 minutes of shaking), with peak ground accelerations exceeding half the force of gravity. Like San Francisco's infamous Nimitz Freeway that collapsed in the 1989 Loma Prieta earthquake, Seattle has double-decker freeways built on tidal flat deposits and uncompacted landfill-deposits that are prone to severe shaking and liquefaction during earthquakes, potentially leading to highway collapse. Faults have recently been discovered running through downtown Seattle, suggesting that the region may be susceptible to strong earthquakes. The Seattle fault runs through Puget Sound, then close to the Kingdome in downtown, and appears

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to have accommodated about 20 feet (6 m) of movement of a block measuring 10 miles (16 km) long by four miles (6.4 km) wide about 1,000 years ago. Shallow faults like this one have the potential to generate devastating earthquakes since their energy is released near the surface, generating large amounts of ground shaking. Other geologic and natural features in the Seattle area all indicate that a major earthquake occurred here, such as landslide scars that mar many hillsides, some of which dammed valleys and formed lakes. Forests now observed on the bottoms of lakes died between 800 and 1,400 years ago, perhaps from drowning associated with earthquake-induced changes in ground level. Sand deposits from tsunamis that inundated bayhead marshes have been tentatively correlated with a sudden uplift of parts of Puget Sound by more than 20 feet (6 m) sometime between 500 and 1,700 years ago during a catastrophic earthquake, and other areas record sudden subsidence of about 5 feet (1.5 m) at 1,000 years ago.

Even more devastating would be an earthquake along the Olympia subduction zone, with potential magnitudes exceeding 9. In addition to tremendous ground shaking, huge tsunamis could be generated that would quickly sweep along the coastline. Sand layers in coastal swamps attest to a succession of tsunamis in the region as recently as 300 years ago, though research is only beginning on these to understand their frequency and whether they were generated from local or distant earthquakes. Some coastal forests with Sitka spruce are dead, having been killed 300 years ago when the land dropped six to eight feet (1.8–2.5 m), putting the roots of the trees into saltwater, killing them. The potential for great (magnitude greater than 9) earthquakes in the Cascadia subduction zone is clear, but the cities of Seattle, Portland, and regions in Washington, British Columbia, Oregon, and northern California are not adequately prepared. Building codes are not as strict as in earthquake-prone southern California, yet the potential for exceptionally large earthquakes is greater in the Pacific Northwest.

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miles (30 km) depth. Geologists now recognize this boundary to be the base of the crust and call it the Mohorovičić (or Moho) boundary and use its seismically determined position to measure the thickness of the crust, typically between 6.2–43.5 miles (10–70 km).

SEISMOGRAPH

Seismographs are sensitive instruments that can detect, amplify, and record ground vibrations, especially earthquakes, producing a seismogram. Numerous seismographs have been installed in the ground throughout the world and form a seismograph network, monitoring earthquakes, explosions, and other ground-shaking events.

The first very crude seismograph was constructed in 1890. While the seismograph could tell that an earthquake was occurring, it was unable to actually record the earthquake. Modern-era seismographs display movements of the Earth by means of an ink-filled stylus on a continuously turning roll of graph paper. When the ground shakes, the needle wiggles and leaves a characteristic zigzag line on the paper. In early models, the ink-filled stylus recorded real movement between the ground and the stylus, and was not very accurate. In recent models, the ink-filled stylus records motions that are detected through modern, ultra-sensitive seismographs, and converted into an electronic signal that is used to move the stylus and make the trace on the paper on the moving drum.

Seismographs are built using a few simple principles of physics. To measure the vibrations of the Earth during an earthquake, the point of reference must be separate from the ground and free from shaking. To this end, engineers have designed an instrument known as an inertial seismograph. These make use of the principle of inertia, which is the resistance of a large mass to sudden movement. When a heavy weight is hung from a string or thin spring, the string can be shaken and the heavy weight will remain stationary. Using an inertial seismograph, the ink-filled stylus is attached to the heavy weight, and remains stationary during an earthquake. The continuously turning graph paper is attached to the ground, and moves back and forth during the quake, resulting in the zigzag trace of the record of the earthquake motion on the graph paper.

Seismographs are used in groups, each recording a different type of motion of the ground. Some seismographs are set up as pendulums and some others as springs, to measure ground motion in many directions. Engineers have made seismographs that can record motions as small as one hundred-millionth of an inch, about equivalent to being able to detect the ground motion caused by a car driving by several blocks away. The ground motions recorded by seismographs are very distinctive, and geologists who study them have methods of distinguishing between earthquakes produced along faults and earthquake swarms associated with magma moving into volcanoes, and even between explosions from different types of construction, accidents, and nuclear blasts. It is even possible to infer the size and other characteristics of different nuclear and other explosions with detailed analysis of the seismic signal from a specific event. Interpreting seismograph traces has therefore become an important aspect of nuclear test ban treaty verification.

In the late 19th century, seismologist and engineer E. Wiechert introduced a seismograph with a large, damped pendulum used as the sensor, with the damping reducing the magnitude of the pendulum's oscillations. This early seismograph recorded horizontal motions using a photographic recording device. Wiechert soon introduced a new seismograph with a mechanical recording device, with an inverted pendulum that could vibrate in all horizontal directions. The pendulum was supported by springs that helped stabilize the oscillations and furthered the productivity of the seismograph. Wiechert's assistant, named Schluter, introduced a vertical recording device. He moved the mass horizontally away from the axis of rotation and maintained it there with a vertical spring. In doing so he was able to record vertical displacement, which helped record many of the complex movements associated with earthquakes.

In the 20th century, seismographs that recorded movements using a pen on a rotating paper-covered drum were introduced, with alternative devices including those that recorded movements using a light spot on photographic film. More sophisticated seismographs can record movements in three directions (up-down, north-south, and east-west), and electronic recording of relative motions is now commonplace.

See also CONVECTION AND THE EARTH'S MANTLE; EARTHQUAKES; MANTLE; PLATE TECTONICS.

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sequence stratigraphy Sequence stratigraphy is the study of the large-scale three-dimensional arrangement of sedimentary strata and the factors that influence the geometry of these sedimentary packages. Sequences are defined as groups of strata that are bounded above and below by identifiable surfaces that are at least partly unconformities. Many sequence boundaries show up well in seismic reflection profiles, enabling their identification in deeply buried rock packages. Sequence stratigraphy differs from classical stratigraphy in that it groups together different sedimentary facies and depositional environments that were deposited in the same time interval, whereas classical stratigraphy would separate these units into different formations. By analyzing the three-dimensional shape of time-equivalent packages, the depositional geometry and factors that influenced the deposition are more easily identified. Some of the major factors that control the shape of depositional sequences include global sea-level changes, local tectonic or thermal subsidence or uplift, sediment supply, and differential biologic responses to subsidence in different climate conditions. For instance, carbonate reefs may be expected to keep pace with subsidence in tropical climates, but to be absent in temperate or polar climates. Sedimentologists and tectonicists use the techniques of sequence stratigraphy in the petroleum industry to understand regional controls on sedimentation and to correlate sequences of similar age worldwide.

See also PASSIVE MARGIN; SEDIMENTARY ROCK, SEDIMENTATION; STRATIGRAPHY, STRATIFICATION, CYCLOTHEM.

Silurian The Silurian refers to the third period of Paleozoic time ranging from 443 Ma to 415 Ma, falling between the Ordovician and Devonian Periods, and the corresponding system of rocks. From base to top it is divided into the Llandoverian and Wenlockian Ages or Series (comprising the Early Silurian) and the Ludlovian and Pridolian Ages or Series (comprising the Late Silurian). The period is named after a Celtic tribe called the Silures, who inhabited a region of Wales where rocks of the Silurian system are well exposed. The Silurian is also known as the age of fishes.

Rocks of the Silurian system are well exposed on most continents, with carbonates and evaporites covering parts of the Midwest of North America, the Russian platform, and China. Silurian clastic sequences form thick orogenic wedges in eastern and western North America, central Asia, western Europe, China, and Australia. Much of Gondwana was together in the Southern Hemisphere, and included the present-day landmasses of South America, Africa, Arabia, India, Antarctica, Australia, and a fragmented China. North America, Baltica, Kazakhstan, and Siberia formed separate landmasses

Fossilized crinoid, or sea lily, in a mudstone deposit, from the Silurian period *(Kaj R. Svensson/Photo Researchers, Inc.)*

in equatorial and northern latitudes. Much of Gondwana was bordered by convergent margins, and subduction was active beneath the Cordillera of North America. Baltica and Laurentia had collided during early stages of the Acadian-Caledonian orogeny, following an arc-accretion event in the Middle to Late Ordovician, known as the Taconic orogeny in eastern North America.

Land plants first appeared in the Early Silurian and were abundant by the middle of the period. Scorpionlike eurypterids and arthropods inhabited freshwater environments and may have scurried across the land. In the marine realm, trilobites, brachiopods, cephalopods, gastropods, bryozoans, crinoids, corals, and echinoderms inhabited shallow waters. Stromatoporoids and rugose and tabulate corals built conspicuous reefs, while jawed fish fed on plankton and nekton.

See also Pleozoic; Phanerozoic.

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Smith, William (1769–1839) English *Geologist*

William Smith was a self-taught surveyor who recognized the regular succession of strata across England and proposed that lithologically similar rock beds could be distinguished by the groups of characteristic fossils embedded within. Using this information, he created the world's first large-scale geologic map of an entire country, showing more than 20 different units, topography, description of the stratigraphy, and structural cross sections. During the same time, Smith produced his works on "Strata identified by organic remains," in which he illustrated the fossils in the rocks through a series of wood engravings. In 1831, the Geological Society of London awarded William Smith the first Wollaston Medal, its highest honor. Since his death, William Smith has become known as the "Father of English Geology."

EARLY YEARS

The eldest of four children, William Smith was born on March 23, 1769, to John and Ann Smith of Churchill, Oxfordshire, England. A blacksmith and a mechanic, John died when William was only eight years old. (Ann remarried a few years later.) As a child he was attracted to the pound stones that he found on Oxfordshire fields. These were round, dome-shaped stones that weighed approximately one pound and were used as a standard weight measure by dairymaids. Sometimes they had an interesting pattern shaped like a five-point star. It turns out that these were fossilized remains of sea urchins. William also collected pundibs, spherical-shaped rocks the size of acorns that actually were the remains of terebratulids, a type of brachiopod. As a suitable substitute for marbles, to young William they were merely play toys, though hindsight shows they were an unrecognized symbol of his future achievements.

CAREER AS A SURVEYOR

William continued studying on his own after leaving the village school, yet had to ask to borrow from his inheritance in order to purchase books. One such book was *The Art of Measuring* by Daniel Fenning. One day when he was 18, he met a man named Edward Webb who was visiting Oxfordshire. He was a professional surveyor, someone who determined boundaries of areas and measured land elevations using geometry and trigonometry. Webb needed an apprentice to help him divide up some farming fields and hired William as an assistant.

Smith learned about the soil and rocks of Oxfordshire and the methods of surveying quickly. Within a few months he could skillfully use a pantograph, a theodolite, dividers, and a great steel chain, all tools for geographic surveying. By the summer of 1788, Smith was doing his own work. He traveled with Webb and eventually moved in with Webb's family 10 miles away at Stow-on-the-Wold. As he traveled, he kept diaries of his observations, especially geologic findings.

In 1791 Smith traveled to Somerset to do a valuation survey in the village of Stowey, near Bath. He ended up staying there and working for Webb for a few years, getting to know the terrain and making contacts with the residents. One influential woman he met was Lady Elizabeth Jones, whose land he originally came out to survey. He rented a farmhouse from her called Rugborne, on the eastern side of High Littleton. This estate later became known as the birthplace of geology.

Somerset was a coal mining community, and Lady Jones was the director of the High Littleton Coal Company. Under her employment, Smith surveyed, planned, and drained land. In 1792 his main work site was the Mearns Pit. The first time Smith went into that mine, he was puzzled by what he observed. As he descended into the mine, he passed grass, gravel, and topsoil, and then a more solid rock layer consisting of limestone, marlstone, and shales. Below this rocky layer was an abrupt transition. The color suddenly changed from reddish green to grayish brown, and there was a surprising, deep, downward slope. This layer was warped and all broken up, in sharp contrast to the nicely laid out horizontal sheets of varying thicknesses in the upper layers. Something very different had controlled the arrangement of layers below the flat coal in the upper part of the mine, and William Smith was determined to figure out what caused such differences.

Approximately 300 million years ago, the European and African tectonic plates collided with each other, forming Pangaea. an enormous former supercontinent composed of all the existing continents. The resulting contraction and folding persisted for millions of years, forming many geological structures such as numerous folds and faults throughout Britain, including the folds and faults that William Smith observed in the coal mine. This process was called the Variscan Orogeny, and it left a complexly deformed mess of pre-Permian rocks. It also made coal mining difficult in north Somerset since rocks containing useful coal were deposited during the Upper Carboniferous period, 290–320 million years ago.

During his time in the mines, Smith made other astute observations. For example, he found the same pattern in mine after mine. From top to bottom, this pattern was sandstone, siltstone, mudstone, nonmarine bands, marine bands, coal, seat earth, and then back to sandstone, in a cyclical pattern. Particular seams of coal were always located in the same relative position. He also noticed that all sedimentary rocks laid down at the same time were similar and that the same fossil types appeared in the same stratigraphical order. Smith began to view geology as more of a science, his interest grew, and he formulated many scientific questions that he next began to test. Smith inquired if the patterns he observed in the coal mine could be applied to other rocks which lay below the ground but miles away, and what if any relationships the rocks underground had to rocks above the ground such as in mountains. He started to use his observations to predict where certain rock types could be found in other places.

Meanwhile, the miners were fretful. Across the Avon River, the Welsh were building a canal to help transport their coal. Somerset could not compete for coal sales if they could not move their coal efficiently, so they decided to build a canal as well. A surveyor was needed to determine the best route for what was to be called the Somerset Coal Canal. The canal eventually connected Limpley Stoke, at a junction with a larger canal, to Camerton, where the coal was located.

A Scotsman named John Rennie initially signed up to make the survey, but he was too busy. Lady Jones suggested Smith as an apprentice. In 1793 Smith started inspecting the structure of the land to choose a route for the canal that would be easy to dig and retain water. This was a wonderful opportunity for him to collect geologic information from the rock exposed by the digging. He eventually recommended that two parallel canals be built, a northerly Dunkerton Line and a southerly Radstock Line. This allowed him to examine the geology of even more land area. He noticed a uniform dip to the rocks between Dunkerton and Midford. This taught him that strata did not always exist as horizontal lines. He also observed that there was a distinctive sequence to the rock layers and was anxious to learn if his ideas and observations applied to the entire nation.

In early 1794, Smith traveled to London as a witness before Parliament in order to obtain authorization to build the canal. This was simply a bureaucratic process necessary before commencing with the project. He had a lot of spare time while in London, and he spent it at libraries and bookstores trying to learn if anyone else had published anything similar to the ideas that were forming in his mind. He was unsuccessful but still worried that someone else might be developing similar ideas to his own.

THE BIRTH OF STRATIGRAPHY

Smith took a carriage trip with two other members of the canal committee later that year. The purpose of the 900-mile (1,448-km) trip over England and Wales was to see how others were building canals. While on this excursion, he continually jumped off the stagecoach to take samples of rock and fossils and took frequent notes of geologic observations. He commented to his companions that he could tell from the landscape just what type of rock lay underneath. He demonstrated this skill to the older men, who were no doubt amused by his enthusiasm.

Smith was becoming quite skilled at identifying different strata, but some strata looked very similar. If rock layers were deposited under the same conditions, even if during different time periods, they can look alike. Likewise, rock layers that were deposited at the same time and were of similar composition can look different due to physical disturbances such as volcanic activity or sweeping currents. In one instance, Smith had observed separate outcrops of limestone that looked very similar but were separated by great distances, representing long periods of time. In addition, his knowledge of dip and strike had convinced him they were in fact different strata from different time periods. Dip is the angle by which a rock layer deviates from the horizontal plane, and strike is the direction 90 degrees to the dip. So, how could one distinguish these rock layers? After years of careful examination of the terrain across England, Smith formulated his principle of fossil succession, which he memorialized by writing in his journal of 1796.

The principle of fossil succession states that the sequence of fossils in rock strata is so regular, that fossils can be used to identify the rocks in which they are embedded. Fossils can be used to establish the time sequence by which the rocks were laid. This was a new concept for geologists in the early 1800s, but today it is a basic principle of stratigraphy. Around the same time, Georges Cuvier and Alexandre Brongniart also were recognizing the utility of fossils in geologic chronologies.

In 1798 Smith purchased a home near Bath called the Tucking Mill. Bath was uniquely suited for geological study since the Middle Jurassic rock outcrop was blatantly exposed. Many strata were apparent, including outcrops of rocks spanning several time periods. While living there, he created what is technically considered the first true geological map, a circular map with a five-mile (8-km) radius and Bath at its center. Smith noted the locations of different fossil types, and used dip and strike information to estimate locations of various strata. Significantly, he used color to specifically depict the locations of oolite (yellow), lias (dirty blue) and red marls (brick red).

Smith was suddenly fired from the Somerset Canal Company in 1799 for an unknown reason. He worked as an independent mineral surveyor and drainage engineer for the next two decades. His expertise was in constant demand, and he made decent money, but unfortunately, most of his earnings were spent on a project that occupied him until 1815, the construction of a large-scale geologic map.

Smith was elected to the Bath Agricultural Society in 1796. This association led to many connections that had later influences on Smith's life and accomplishments. Two encouraging members, Reverend Benjamin Richardson of Farleigh and Reverend Joseph Townsend of Pewsey, were also fossil collectors. One night in 1799, the clerics pulled out some paper and wrote out, as Smith dictated, a list of strata. This was in the form of a table that included information not only on the succession of 23 strata from chalk to coal, but their thicknesses, lithologic characteristics, and distinguishing types of embedded fossils. They made three copies of the table that night, one for each of them, with the understanding that the men would recopy and disseminate this information to whoever was interested. Years later, Smith heard that copies of this table were being distributed on different continents.

In 1801 Richardson suggested that Smith write a prospectus, outlining his intent to publish a work on the natural order of strata in England and Wales. He obtained the sponsorship of Sir Joseph Banks, the president of the Royal Society of London, for this project. Years passed, however, and no progress was made. Smith was too busy working, trying to make enough money to pay his mortgages.

In 1805 Smith had leased a large house in London. Being of common birth and never formally educated, he felt it was important to keep up appearances of success in order to obtain respectable employment and sponsorship; however, he still owned his Tucking Mill estate. In addition, he had made a bad investment a few years earlier. He took out a second mortgage on Tucking Mill to invest in a quarry for the excavation of oolitic limestone, a popular building material. Unfortunately, times were bad, and in the early 1800s people stopped building altogether. Furthermore, the quality of the stone was inferior. Smith also rented an office in Bath, serving as his base for a brief partnership he had in a firm, Smith and Cruse, Land Surveyors. At the expense of his long-awaited mapping project, he furiously toiled away just trying to make ends meet.

In the midst of this, Smith got married. His 17-year-old bride, Mary Ann, was uneducated, often physically ill, and eventually became mentally deranged, adding to Smith's troubles. In 1807 he became the guardian of his orphaned nephew, John

Phillips. John later became Smith's assistant and then a notable geologist, but at the time he was another financial burden.

THE WORLD'S FIRST GEOLOGIC MAP

John Cary, a highly regarded English cartographer, agreed to publish Smith's map in 1812. A topographical map was engraved, on top of which Smith added his geological information. The actual construction of the map was quite a task itself, involving 16 engraved plates and three years to accomplish. The data collection and assimilation of the information took Smith 14 years to complete. The completed map, *A Delineation of the Strata of England and Wales, with Part of Scotland,* was published in 1815 with a 50-page textual explanation.

The map was slightly larger than eight by six feet (2.4 by 1.8 m) with the scale being five miles (8 km) to one inch (2.54 cm). One striking feature was the color. Smith used a variety of shades to depict certain types of rock: gray for Tertiary outcrops, blue green for chalk, brown for coral rag and carstone, yellow for oolites, blue for lias, and red for red ground. Not only was the use of color original, but he colored the base of each rock formation darker than its top. Thus, if one stood back, an immediate pattern was apparent. This piece of work became a classic in cartography. Modern geological maps use the same principles and even the same color scheme that Smith used almost 200 years ago.

Four hundred copies were made, but they sold poorly, partly due to George Bellas Greenough, one of the original founders of the Geological Society of London, a small, elite club of rich intellectuals. Though Smith was hurt by the lack of inclusion in their society, in 1808 he had invited them to view his impressive fossil collection, which was carefully organized by chronological succession and beautifully displayed on a series of sloping shelves meant to represent the sequence of strata. The visit of the Geological Society was a disappointing one. Smith received neither the praise he deserved nor the invitation to join the Society that he so desperately craved. Little did he know that the president of the society was not only impressed but also jealous. Greenough was about to embark on a mission of scientific pilfering that would be personally and professionally catastrophic to Smith.

Greenough announced the intention of the Geological Society to publish a geologic map of England, similar to Smith's. Potential buyers of Smith's map decided to wait until Greenough's map was published rather than buy Smith's map. After all, Smith's did not have the backing of the Geological Society, and Greenough's promised to be cheaper. When the map did come out in 1819, it did not fare much better than Smith's map, nor did it contain any new information. Later Greenough was forced to admit that he stole much of Smith's work in constructing his map. In a ridiculous effort to make amends, Greenough apologized and presented a copy of his map to Smith.

Financial troubles intensified, and Smith was forced to sell his extensive fossil collection to the British Museum (the present-day Natural History Museum of London). In hopes of earning a little money, Smith published *Strata Identified by Organized Fossils* (1816) and *Stratigraphical System of Organized Fossils Part I* (1817). The latter was a catalog of the collection now owned by the museum. Neither sold well, and he continued creating and publishing geologic maps of several counties in England (1819–24). He also released *A Geological Section from London to Snowdon* (1817), showing the relative thicknesses and arrangements of rocks. In 1819, unfortunately, his financial difficulties became too great. He was sent to debtor's prison for 11 weeks, during which time he lost his home and his few remaining personal belongings. He would have lost his papers and maps too, but an anonymous friend purchased and returned them to Smith. After his release, he gathered his sickly wife and his nephew and moved away from London, where he had been so horribly treated, into obscurity, where he remained for the next 12 years.

They traveled to Yorkshire, where Smith enjoyed lecturing on geology, but he had to give this up due to poor health. He settled in Scarborough from 1824 to 1828 and continued to study geology. He also designed a museum and helped with the town water supply.

RESPECTED AT LAST

Sir John Vanden Bempde Johnstone hired Smith as his land steward in Hackness in 1828. Johnstone was a member of the Geological Society and a fossil collector himself. He was aware of Smith's accomplishments, and with the assistance of a friend, he championed for an annuity to be purchased for the aging geologist.

In 1831 Smith was awarded the first Wollaston Medal by the Geological Society of London in recognition of his research into the mineral structure of the Earth. In return, Smith presented the Society with his original table of 23 strata (1799), his colored geologic map of Bath and the surrounding area (1799), and an original rough sketch of his geologic masterpiece (1801). He received his gold medal the next year followed by a government pension. Trinity College in Dublin awarded him an honorary doctorate degree in 1835.

Smith's last job was serving as part of a committee selected by the government to choose the new building material for the British House of Parliament, as the old building had burned down in 1834. The committee selected a magnesium limestone from a quarry in Derbyshire. The supply ran short, and a quick substitution had to be found. The substitute stone turned out to be unsuitable. One wonders if Smith might have recognized this and corrected the error before it was too late, if he had lived longer. Within 10 years, the exterior of the buildings deteriorated.

On the way to a British Association meeting in Birmingham, Smith stopped to visit a friend in Northampton. He caught a cold that turned fatal. The father of English geology died on August 28, 1839. He was buried nearby in Saint Peter's Church.

Smith freely shared his knowledge of England's geology. His geologic maps were practically applied to the fields of mining, agriculture, road building, water draining, and canal building. His 1815 map of England and Wales is considered a milestone in geological cartography. Though Smith's major accomplishments went unnoticed by the scientific community initially, Smith's contributions to geography and biostratigraphy were just beginning at be recognized at the time of his death. In 1865 the Geological Society added Smith's name to Greenough's map, rightfully acknowledging his intellectual contribution. The Geological Society and the Oxford Museum display busts of Smith, and signposts and plaques adorn his former residences. Since 1977 the Society has awarded the William Smith Medal for contributions to applied and economic aspects of geology. The man who revealed his vision of the underworld has finally received the recognition he deserves.

See also EUROPEAN GEOLOGY; STRATIGRAPHY, STRATIFICATION, CYCLOTHEM.

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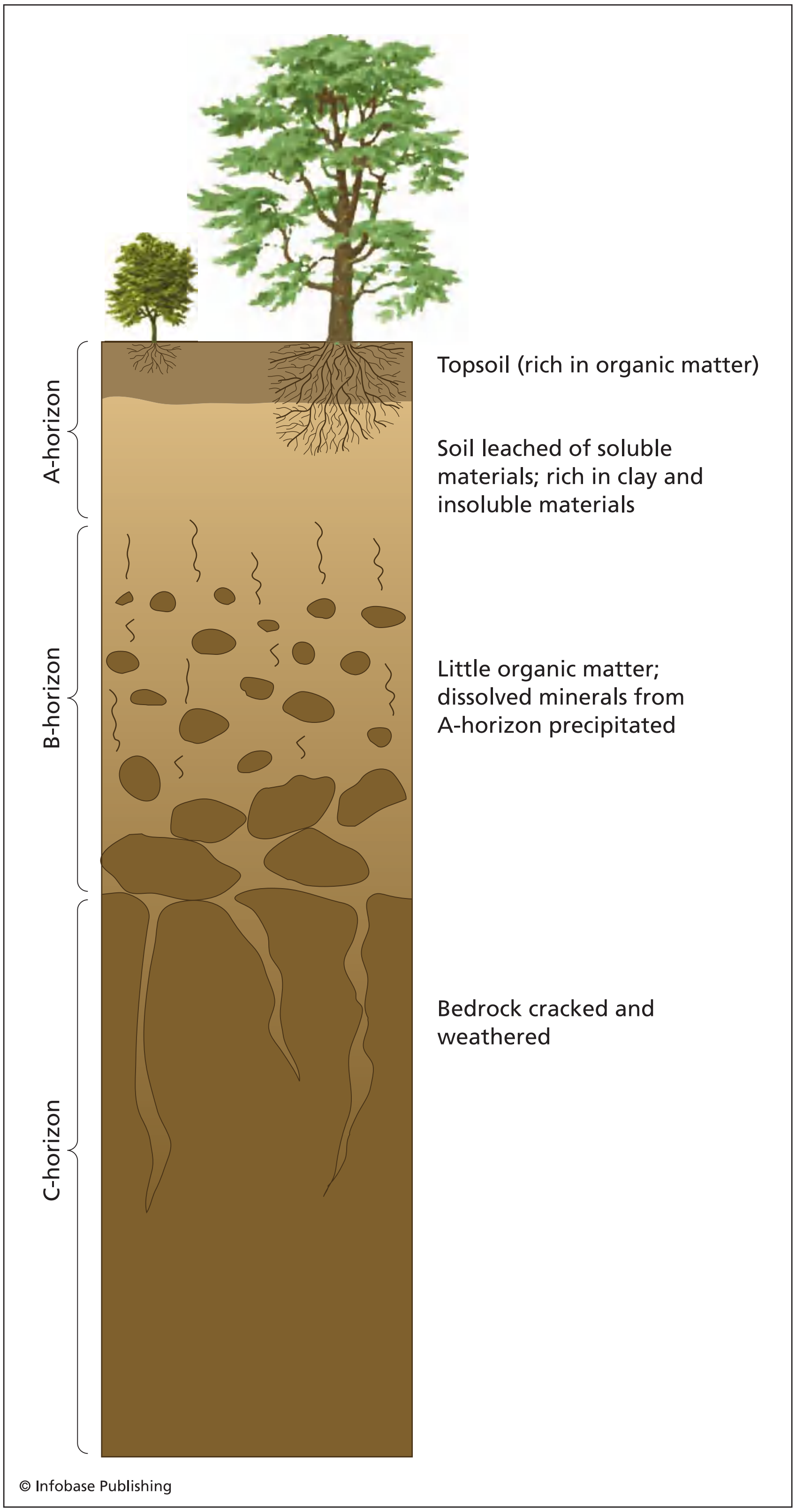
soils Soils include all the unconsolidated material resting above bedrock and serve as the natural medium for plant growth. Differences in soil profile and type result from differences in climate, the type of the original rock source, the types of vegetation and organisms, topography, and time. Normal weathering produces a characteristic soil profile, marked by a succession of distinctive horizons in a soil from the surface downward. The A horizon is closest to the surface, and usually has a gray or black color because of high concentrations of humus (decomposed plant and animal tissues). The A horizon typically loses some substances through downward leaching. The B horizon is commonly brown or reddish, enriched in clay produced in the same place that the rock it was weathered from was located, and transported downward from the A horizon. The C horizon of a typical soil consists of slightly weathered parent material. Young soils regularly lack a B horizon, and the B horizon grows in thickness with increasing age.

Peat layer over bedrock in a cliff near Quito, Ecuador *(Dr. Morley Read/Photo Researchers, Inc.)*

Some unique soils form under unusual climate conditions. Polar climates are typically cold and dry, and the soils produced in polar regions are typically well drained and lack an A horizon, sometimes underlying layers of frost-heaved stones. In wetter polar climates, tundra may overlie permafrost, which prevents the downward draining of water. These soils are saturated in water and rich in organic matter. These polar soils play a crucial role in maintaining the global environment. They contain an abundance of organic material, effectively isolating it from the atmosphere and locking up much of the planet's carbon. Cutting down of northern forests as is occurring in Siberia may affect the global carbon dioxide budget by releasing much of this organic material as carbon dioxide to the atmosphere, possibly contributing to climate change and global warming.

Dry climates limit the leaching of unstable minerals, such as carbonate, from the A horizon. Leaching may also be impeded by evaporation of groundwater. Extensive evaporation of groundwater over prolonged times leads to the formation of caliche crusts. These are hard, generally white carbonate minerals and salts that were dissolved in the groundwater but precipitated when the groundwater moved up through the surface and evaporated, leaving the initially dissolved minerals behind.

In warm, wet climates, most elements (except for aluminum and iron) are leached from the soil profile, forming laterite and bauxite. Laterites, which are typically deep red in color, are found in many tropical regions. Some of these soils are so hard that they are used for bricks.



Typical soil profile, showing organic zone, and the A, B, and C horizons

Soils form at various rates in different climates and other conditions, ranging from about 50 years in moderate temperatures and wet climates, to about 10,000 to 100,000 years for a good soil profile to develop in dry climates, such as the desert southwest of the United States. Some mature soils, such as those in the tropics, have been forming for several million years. Deforestation causes soil erosion, which cannot be repaired easily. In many places, such as parts of Madagascar, South America, and Indonesia, deforestation has led to accelerated rates of soil erosion, removing thick soils that have been forming for millions of years. These soils supported a rich diversity of life, and it is unlikely that the soils will ever be restored in these regions.

See also MASS WASTING; WEATHERING.

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solar system The Earth's solar system represents the remnants of a solar nebula that formed in one of the spiral arms of the Milky Way galaxy. After the condensation of the nebula, the solar system consisted of eight major planets, the moons of these planets, and many smaller bodies in interplanetary space. From the Sun outward, these planetary bodies include Mercury, Venus, Earth, Mars, the asteroids, Jupiter, Saturn, Uranus, and Neptune. The physical properties of these bodies are listed in the table "Physical Properties of Objects in the Solar System." Until 2006 Pluto was regarded as a planet, but in 2006 a team of astronomers voted that Pluto did not meet the criteria of being a planet in that its orbit was too erratic and its size too small, and demoted Pluto to the status equivalent of a captured asteroid. Most asteroids are concentrated in a broad band called the asteroid belt located between the orbits of Mars and Jupiter. Although none of the asteroids are larger than the Earth's moon, they are considered by many to be "minor planets," since they are orbiting the Sun.

The asteroids are small rocky, metallic bodies, most of which orbit in the asteroid belt located between Mars and Jupiter, although some have different erratic orbits. Others are located in different belts further from the Sun. Comets include icy bodies and rocky bodies, and are thought by many astronomers to be material left over from the formation of the solar system that was not incorporated into any planetary bodies. Thus, comets may have clues about the early composition of the solar nebula.

The planets and asteroids orbit the Sun counterclockwise when viewed from above the Earth's North Pole, and most have roughly circular orbits that are confined to a relatively flat plane called the ecliptic plane. The spacing between the different orbits increases with increasing distance from the Sun. The inner four planets (Mercury, Venus, Earth, and Mars), referred to as the terrestrial planets, have densities and properties that are roughly similar to Earth and are generally rocky in character. In contrast the outer planets (Jupiter, Saturn, Uranus, and Neptune), known as the Jovian planets, have much lower densities and are mostly gaseous or liquid in form. The Jovian planets are much more massive than the terrestrial planets, rotate more rapidly, have stronger magnetic fields than the terrestrial planets, and have systems of rings that circle the planets.

FORMATION OF SOLAR SYSTEM

The solar system began to form from a spinning solar nebula about 5 billion years ago, 9 billion years after the universe started expanding from nothing in the big bang some 14 billion years before the present. This solar nebula consisted of a mass of gas, dust, and fragments that began spinning faster as gravitational forces caused the material to collapse on itself. Temperatures ranged from extremely hot in inner parts of the solar nebula to cold in the outer reaches. Planets began accreting by accumulating more and more dust and small fragments to form the bigger

PHYSICAL PROPERTIES OF OBJECTS IN THE SOLAR SYSTEM

Object	Orbital Distance (AU)	Mass (earths)	Diameter (Earths)	Rotational Period (Days) (- Means Retrograde)	Orbital Period (Years)	Density (Earths)	Surface Gravity (Earths)	Moons
Sun	0.0	332,000	109.2	25.8	. . .	1.42	28	. . .
Mercury	0.39	0.06	0.38	59	0.24	0.98	0.38	0
Venus	0.72	0.81	0.95	-243	0.62	0.95	0.90	0
Earth	1.0	1.00	1.00	1.00	1.0	1.00	1.00	1
Mars	1.5	0.11	0.53	1.03	1.9	0.71	0.38	2
Ceres asteroid	2.8	0.0002	0.07	0.38	4.7	0.38	0.03	0
Jupiter	5.2	317.8	11.2	0.42	11.9	0.24	2.34	63
Saturn	9.5	95.2	9.5	0.44	29.5	0.12	1.16	60
Uranus	19.2	14.5	4.0	-0.69	83.7	0.23	1.15	27
Neptune	30.1	17.2	3.9	0.72	163.7	0.30	1.19	13
Pluto (dwarf planet)	39.5	0.002	0.18	-6.40	248.0	0.37	0.04	3
Eris (dwarf planet discovered June 2007)	67.7	0.002	0.18	~8	557	?	?	1

planetesimals that began rotating around the large mass accumulating as the Sun at the center of the disk. These early planetesimals grew into protoplanets, still experiencing many impacts with large asteroids and comets by 4.56 billion years ago. As the main planets formed, they differentiated into core-mantle-crust systems, and in the late bombardment period from about 4.5–3.5 billion years ago, these planets suffered many impacts with large asteroids and comets. Several large, differentiated bodies in what is now the asteroid belt were destroyed by large impacts, forming billions of fragments that now form the bulk of meteorites that hit the Earth. The inner planets are made dominantly of silicate minerals and are called the rocky or terrestrial planets, whereas the outer planets are mainly gaseous, often called the Jovian planets after the largest body, Jupiter. Comets come from further out in the solar system, most from beyond the orbit of Neptune in a region called the Oort Cloud.

See also ASTEROID; ASTRONOMY; COMET; EARTH; GALILEI, GALILEO; JUPITER; MARS; MERCURY; NEPTUNE; ORIGIN AND EVOLUTION OF THE EARTH AND SOLAR SYSTEM; PLUTO; SATURN; URANUS; VENUS.

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Sorby, Henry Clifton (1826–1908) British ***Geologist, Biologist, Microscopist, Metallurgist*** Henry Sorby was a well-known British scientist whose most influential scientific work was done from 1849–64. His work was based on the application of the microscope to geology and metallurgy. In these two fields, his work included simple quantitative observation and the building and meticulous use of new experimental equipment and interpretation based on the application of elementary physicochemical principles to complex natural phenomena. His goal was to "apply experimental physics to the study of rocks." Sorby's most famous achievement was the development of the basic techniques of petrography by using the polarizing microscope to study the structure of thin rock sections.

Henry Sorby was born in Woodbourne near Sheffield in Yorkshire on May 10, 1826, and died March 9, 1908. He attended the Sheffield Collegiate School, where he developed a keen interest in natural sciences, especially geography, and began to study some of the excavated valleys of Yorkshire. In these studies he became interested in the older geological periods, sedimentary layers, and the formation of structures during the deformation of these rocks. He began working on sedimentary rocks, and by 1851 he was involved in a debate on the origin of slaty cleavage. His paper "On the Origin of Slaty Cleavage" in 1853 showed that cleavage was a result of the reorientation of particles of mica accompanying the deformation flow of the deposit under anisotropic pressure. Basically Sorby demonstrated that when a rock is flattened by deformation, the flat mica grains tend to rotate so that most of them are close to parallel, forming the planar structure called slaty cleavage in the rocks. This work was followed by the publication in 1858 of an important memoir in the *Quarterly Journal of the Geological Society of London,* which Sorby titled "On the Microscopical Structure of Crystals." He went on to study organisms in limestone and discussed the significance of microorganisms in chalk. Sorby then moved from slate to schist and metamorphic rocks in general. His paper on liquid inclusions in crystals, both natural and artificial, was very important since later study of these inclusions yielded information about the pressure and temperature conditions during the deformation and metamorphism of these and other rocks. His use of the microscope helped him to find abundant smaller inclusions within the microcrystals of many metamorphic rocks.

Henry Sorby was a member of the Royal Microscopic Society and was awarded the Wollaston Medal by the Geological Society of London in 1869, the highest award given by that society. In 1882 he was elected president of Firth College in Sheffield. The International Association of Sedimentologists and the Yorkshire Geological Society both have Sorby Medals, named after Henry, and award these to individuals with outstanding achievements in geology.

See also SEDIMENTARY ROCK, SEDIMENTATION; STRUCTURAL GEOLOGY.

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South American geology South America has a diverse and long geological history. The Andean Mountain chain on the western side of the continent has been active for a couple of hundred million years since before the breakup of Gondwana, with most activity in the Mesozoic-Cenozoic-Tertiary recent times, and it is still one of the world's most active continental margin arcs. These ranges are drained by the Amazon and Paraná River systems, which cut through other ranges including the Pampean, Austral, and Tandilia ranges. In the north, the Caribbean oceanic plateau, formed by the Caribbean mountain system and the Andean Cordillera in the northwest, is in an oblique collision with the South American continent. The southern boundary of South America is marked by the Magellan mountain system and the Falkland Plateau to the southeast.

The core of the South American continent consists of the Precambrian Guiana and Brazilian shields and the Río de la Plata craton. The Guiana shield is bordered, in subsurface strata, on the north and northeast by gently folded Paleozoic strata, and by metamorphic belts in the south and northwest. The Brazilian shield is bordered in the north along the Amazon basin by gently folded Paleozoic strata, and by Paleozoic and Mesozoic strata in the east.

Landsat satellite image of South America *(Bill Howe/Alamy)*

ANDES

The Andean mountain chain is a 5,000-mile- (8,000-km-) long belt of deformed igneous, metamorphic, and sedimentary rocks in western South America, running generally parallel to the coast, between the Caribbean coast of Venezuela in the north and Tierra del Fuego in the south. Some sections are characterized by active volcanoes, others by their absence. Most of the Andes are located above the subducting Nazca plate except for the southern Andes, which are located above the subducting Antarctic plate. The mountains merge with ranges in Central America and the West Indies in the north, and with ranges in the Falklands and Antarctica in the south. Many snow-covered peaks rise higher than 22,000 feet (6,000 m), making the Andes the second largest mountain belt in the world, after the Himalayan chain. The highest range in the Andes is the Aconcagua on the central and northern Argentine-Chile border. The high cold Atacama Desert is located in the northern Chile sub-Andean range, and the high Altiplano Plateau is situated along the great bend in the Andes in Bolivia and Peru.

The southern part of South America consists of a series of different terranes added to the margin of the Gondwanan supercontinent in the late Proterozoic and early Paleozoic. Subduction and the accretion of oceanic terranes continued through the Paleozoic, forming an accretionary wedge 155 miles (250 km) wide. The Andes formed as a continental margin volcanic arc system on the older accreted terranes, above a complex system of subducting plates from the Pacific Ocean. They are geologically young, having been uplifted mainly in the Cretaceous and Tertiary, with active volcanism, uplift, and earthquakes. The specific styles of volcanism, plutonism, earthquakes, and uplift are found to be segmented strongly into seven main zones in the Andes and related to the nature of the subducting part of the Nazca plate, including its dip and age. Where the subducting slab dips more than 30 degrees beneath South America, the Andes have active volcanism on the surface. In contrast, regions above places where the subduction zone is sub-horizontal do not have active volcanoes, but instead have contraction and sedimentary basin formation.

Although the history of the Andes extends back into the Paleozoic with the accretion of different terranes, especially in the southern parts of the mountain belt, most of the current-day Andean ranges were formed in Mesozoic to recent times. The dominant processes in their formation are related to their location on the leading edge of the convergent plate boundary between South America and the Nazca plate.

Simple geological map of South America showing the location of the Archean cratons, including the Amazonian craton (AM), São Francisco craton (SF), Rio de la Plata craton (RP), Sao Luis cratonic fragment (SL), Luis Alves cratonic fragment (LA). Late Proterozoic orogens and basins surrounding these cratons. The Andean belt forms the western side of South America and includes some Precambrian outcrops (shown in purple). Younger basins including the Amazona, Paraná, and Parnaiba contain thick sequences of Phanerozoic sediments and are drained by large rivers including the Amazon, Río Negro, and Paraná.

Altiplano

The Altiplano is a large uplifted plateau in the Bolivian and Peruvian Andes of South America. The plateau has an area of about 65,536 square miles (170,000 km^2) and an average elevation of 12,000 feet (3,660 m) above sea level. The Altiplano is a sedimentary basin caught between the mountain ranges of the Cordillera Oriental on the east and the Cordillera Occidental on the west. Lake Titicaca, the largest high-altitude lake in the world, is located at the northern end of the Altiplano, a dry region with sparse vegetation and scattered salt flats. Villagers grow potatoes and grains, and a variety of minerals are extracted from the plateau and surrounding mountain ranges.

The Atacama Desert is an elevated arid region located in northern Chile, extending over 384 square miles (1,000 km^2) south from the border with Peru. The desert is located 2,000 feet (600 m) above sea level and is characterized by numerous dry salt basins (playas), flanked on the east by the Andes and on the west by the Pacific coastal range. The Atacama is one of the driest places on Earth, with no rain ever recorded in many places, and practically no vegetation in the region. Nitrate and copper are mined extensively in the region.

The Atacama is first known to have been crossed by the Spanish conquistador Diego de Almagro in 1537, but it was ignored until the middle 19th century, when mining of nitrates in the desert began. However, after World War I, synthetic nitrates were developed and the region has been experiencing economic decline ever since, as it is too expensive to mine the natural nitrates from the desert.

AMAZON RIVER

The Amazon is the world's second-longest river, stretching 3,900 miles (6,275 km) from the foothills of the Andes to the Atlantic Ocean. The Amazon begins where the Ucayali and Marañon tributaries merge, and it drains into the Atlantic near the city of Belém. The Amazon carries the most water and has the largest discharge of any river in the world, averaging 150 feet (45 m) deep. Its drainage basin amounts to about 35 percent of South America, covering 2,500,000 square miles (6,475,000 km^2). The Amazon lowlands in Brazil include the largest tropical rainforest in the world. In this region, the Amazon is a muddy, silt-rich river with many channels that wind around numerous islands in a complex maze. The delta region of the Amazon is marked by numerous fluvial islands and distributaries, as the muddy waters of the river get dispersed by strong currents and waves into the Atlantic. A strong tidal bore, up to 12 feet (3.7 m) high, runs up to 500 miles (800 km) upstream.

Waters of the Amazon River flow through a sediment-filled rift basin, between the Precambrian crystalline basements of the Brazil and Guiana shields. The area hosts economic deposits of gold, manganese, and other metals in the highlands, and detrital gold in lower elevations. Much of the region's economy relies on the lumber industry, with timber, rubber, vegetable oils, Brazil nuts, and medicinal plants sold worldwide.

Spanish commander Vincent Pinzon in 1500 was probably the first European to explore the lower part of the river basin, followed by the Spanish explorer Francisco de Orellana in 1540–41. Orellana's tales of tall strong female warriors gave the river its name, borrowing from Greek mythology. Further exploration by Pedro Teixeira, Charles Darwin, and Louis Agassiz led to greater understanding of the river's course, peoples, and environment settlements did not appear until steamship service began in the middle 1800s.

THE MAGELLAN RANGES, CAPE HORN, AND THE FALKLAND PLATEAU

The southern tip of South America has consistently horrid weather with high winds, rain and ice storms, and large sea waves. Southernmost South America is a large island archipelago known as Tierra del Fuego, separated from the mainland by the Strait of Magellan, and the southern tip of which is known as Cape Horn. The Drake Passage separates Cape Horn from the northern tip of the Antarctic Peninsula. Tierra del Fuego and the Strait of Magellan were discovered by Magellan in 1520 and settled by Europeans, Argentineans, and Chileans after the discovery of gold in the 1880s. These peoples brought diseases that spread to and killed off all of the indigenous people of the islands.

The Falkland Plateau is a shallow-water shelf extending 1,200 miles (2,000 km) eastward from Tierra del Fuego on the southern tip of South America, past South Georgia Island. The plateau includes the Falkland Islands 300 miles (480 km) east of the coast of South America and is bounded on the south by the Scotia Ridge and on the north by the Agulhas-Falkland fracture zone. The Falkland Islands include two main islands (East and West Falkland) and about 200 small islands and are administered by the British but also claimed by Argentina, with the capital at Stanley. The islands are stark rocky outposts, plagued by severe cold rains and wind, but have abundant seals and whales in surrounding waters. The highest elevation is 2,315 feet (705 m) on Mount Adam. Thick peat deposits support a sheep-farming community among the dominantly Scottish and Welsh population.

The Falkland Plateau formed as a remnant of the southern tip of Africa that remained attached to

South America during the breakup of Gondwana and the movement of South America away from Africa. The Agulhas-Falkland fracture zone extends to the tip of Africa and represents the transform along which divergence of the two continents occurred. Numerous Mesozoic rift basins on the plateau are the site of intensive oil exploration. The geology of the Falklands was first described by Charles Darwin from his expedition with the HMS *Beagle* in 1833 and reported in 1846, and Johan G. Andersson completed later pioneering studies.

Precambrian granite, schist, and gneiss are found on the southwest part of West Falkland Island, probably correlated with the Nama of South Africa. The Precambrian basement is overlain by a generally flat to gently tilted Paleozoic sequence including 1.7 miles (3,000 m) of Devonian quartzite, sandstone, and shale. A Permo-Triassic sequence 2.2 miles (3,500 m) thick unconformably overlies the Paleozoic sequence and includes tillites and varves indicating glacial influence. These rocks are cut by Triassic-Jurassic dioritic to diabasic dikes and sills related to the Karoo and Parana flood basalts. Diamictites and long lobes of gravel interpreted as mudflows deposited in a periglacial environment overlie quaternary interglacial deposits.

The Falklands are folded into a series of northwest-southeast trending folds that intensify to the south and swing to east-west on the east of the plateau.

PRECAMBRIAN CRATONS AND SHIELDS

The core of South America is made of its Precambrian cratons, including the Guiana and Brazilian (also called the Amazonian) shields and the Rio de la Plata craton. These cratonic blocks also formed central regions of several past supercontinents including Gondwana and Rodinia.

The Guiana shield has rocks as old as 3.4 billion years, and other major groups of rocks formed at 1.5 and 0.9 billion years ago. Highland regions of the Guiana shield, called the Guiana Highlands, are characterized by a series of beautiful table-top mountains called *tequis*. These regions host some of the world's most spectacular waterfalls such as Angel Falls, Kaieteur Falls, and Cuquenan Falls. The main part of the Archean section of the Guiana shield is largely confined to the northern part of the shield in Venezuela, where it shows major tectonic and magmatic events at 2.7–2.5 billion years ago in the Aroan-Jaquie event, from 2.2–1.8 billion years ago in the Transamazonian orogeny, at 1.75–1.5 billion years ago in Uruacuan event, then the Parguazan event at 1.5–1.4 billion years ago, the Orinocan-Nickerie event from 1.3–1.2 billion years ago, and 1.0–0.65 billion years ago in the Brazilian orogeny. The older Archean rocks include granulite facies, mafic volcanic rocks, iron-rich cherts, and gneisses cut by granitic intrusives. Most Archean areas are separated from the late Archean and Paleoproterozoic sections by major shear zones. Late Archean rocks include amphibolite-facies belts in both the Guiana and Brazilian shields, with both mafic and ultramafic magmatic rocks in greenstone belts, and with tectonic boundaries with other units.

The Uruacuan event at 1.75–1.55 Ga affected the southern border of the Guiana shield and the north central border of the Brazilian shield and is associated with eruption and deposition of pyroclastic and continental clastic rocks. This was followed by intrusion of granitic plutons from 1.5 to 1.4 billion years ago. Both shields appear to have stabilized around this time, with the intrusion of post-tectonic rapakivi granitoids from 1.75–1.55 billion years ago. Brasiliano events from 1.0–0.9, and from 0.75–0.65 billion years ago later affected the edges of the shields.

A thick platformal sedimentary cover developed over these Precambrian rocks in the Paleozoic, which includes Silurian-Devonian marine sequences, Carboniferous marine and continental deposits, and Permian to Triassic continental rocks in the Parana-Chaco-Amazon region. The Triassic saw active rifting associated with the opening of the Atlantic, with the activation of many faults on the shields. The faulting was associated with tholeiitic magma eruption in the Triassic followed by alkaline ultramafic intrusions in the Jurassic to Eocene in Brazil and Paraguay and is associated with carbonatites and kimberlites.

The Rio de la Plata craton forms a small Archean cratonic block in southeastern South America, mostly in Uruguay. This craton has a core of ancient greenstone belts and gneisses in the Quadrilatero Ferrifero area, with a long complex deformation history. Dikes that cut the craton at 1.73 billion years ago may be related to a mantle plume event.

See also ARCHEAN; CONTINENTAL CRUST; CONVERGENT PLATE MARGIN PROCESSES; CRATON; GREENSTONE BELTS; OROGENY; PALEOZOIC; PLATE TECTONICS; RIVER SYSTEM; STRUCTURAL GEOLOGY.

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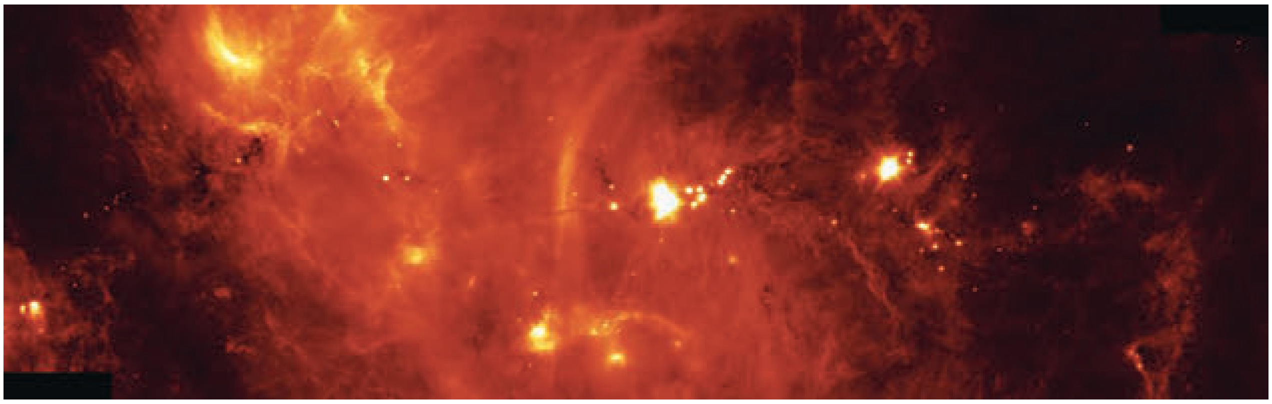
star formation Stars form by the condensation or gravitational contraction of particles in interstellar gas and dust found in giant molecular clouds. As these cold clouds contract, they heat up and eventually become hot enough to stimulate the process of nuclear fusion, at which point a star is born. Although this process sounds simple, the process of star formation involves many uncertainties and unknown triggers. Why do some interstellar clouds collapse to form stars and why do others not collapse? What processes occur in interstellar molecular clouds as they collapse, and what leads to different types of star formation? Some of the answers to these questions relate to variations in the initial molecular clouds, and some relate to events that happen during cloud collapse. One of the main factors is the relative strength of two forces, those of gravity and temperature. Gravitational attraction between atoms in a molecular cloud or any other object is proportional to the masses involved, and since atoms have very low mass the gravitational attraction between atoms can be very small. Temperature of a gas is a measure of the average speed of atoms or molecules in the gas, with higher temperatures equated with higher speeds of the particles. Many processes in the formation of stars relate to the relative strengths of the two effects, and the ability of the force of gravity to overcome the effects of heat. The balance between these forces is also what stops stars from collapsing, since the outward pressure from the heated, fast-moving gases exactly equals the inward pull of gravity in these stars.

Rotation or spin of molecular clouds also acts to oppose the inward pull of gravity. Rotation of molecular clouds causes them to develop a bulge around their center. As the cloud contracts the law of conservation of angular momentum states that it must spin faster, and material in its outer reaches may spin off into outer space. In order for material not to fly off into space an opposing force must be applied to pull the particles inward, and this force is gravity. If the mass of the spinning molecular cloud is great enough to exert a gravitational pull that is greater than the outward force from the spin of the cloud, it will condense further to form a spinning disk. The cloud will eventually flatten out into a pancake shape with a bulge in its center and the bulge will become a star. If there is less mass, then the outward force from the spin may be great enough to cause the cloud simply to disperse with the particles flying off into space.

Most interstellar clouds are also characterized by magnetic fields, which can influence whether or not the cloud condenses into a solar disk. As molecular clouds contract and heat up, the number of collisions between particles increases dramatically, causing the



Birth of stars in a molecular cloud. The shroud of dust shown here in constellation Cygnus hides an exceptionally bright source of radio emission called DR21. Visible light traces reveal no evidence of what is happening in this region because of heavy dust obscuration. NASA's *Spitzer Space Telescope* took this image and is able to peek behind the veil of dust at one of the most massive embryonic stars in the Milky Way galaxy. This star is more than 100,000 times as bright as the Sun. The image also shows a powerful outflow of hot gas emanating from the star and bursting through the molecular cloud. *(NASA)* gas to become ionized. Magnetic fields are generated, and these fields cause particles to move along the magnetic field lines but prevent the particles from moving against the magnetic field, causing the shape of the condensing molecular cloud to become distorted. Since the formation of the charged particles in the densest part of the collapsing cloud is tied to the formation of the magnetic field, the two processes are linked and the magnetic field intensifies and is pulled in toward the center of the condensing cloud. The interactions between these forces are complex and may explain many of the variations in the shapes and other characteristics of condensing molecular clouds and young star systems.

Composition can also affect the way a star evolves and matures. Stars that evolve from interstellar molecular clouds with higher concentrations of heavy elements tend to be cooler and a little less luminous than stars with more light elements.

STAGES TO MAIN SEQUENCE EVOLUTION

Stars that have roughly the same mass as the Earth's Sun follow a similar evolutionary path, much of which lies along a general trend on a diagram of solar luminosity versus surface temperature (this diagram is called a Hertzsprung-Russell [H-R] diagram). The H-R diagram shows how a star's size changes as it evolves with respect to luminosity and temperature over time, with most stars the size of the Sun following a curved S-shaped trajectory across the diagram, called the main sequence of stellar evolution. For about 90 percent of a star's evolutionary history it will burn hydrogen quietly without changing much and will remain close to stationary on the H-R diagram. However, a star's early and late stages of evolution can be quite different from its average or steady-state main-sequence characteristics. The evolutionary stages and track of a star are shown on the H-R diagram through its history of luminosity and surface temperature. Stars with the mass of the Sun go through several stages, from interstellar cloud, to collapsing interstellar cloud fragment, to protostar, to main sequence star.

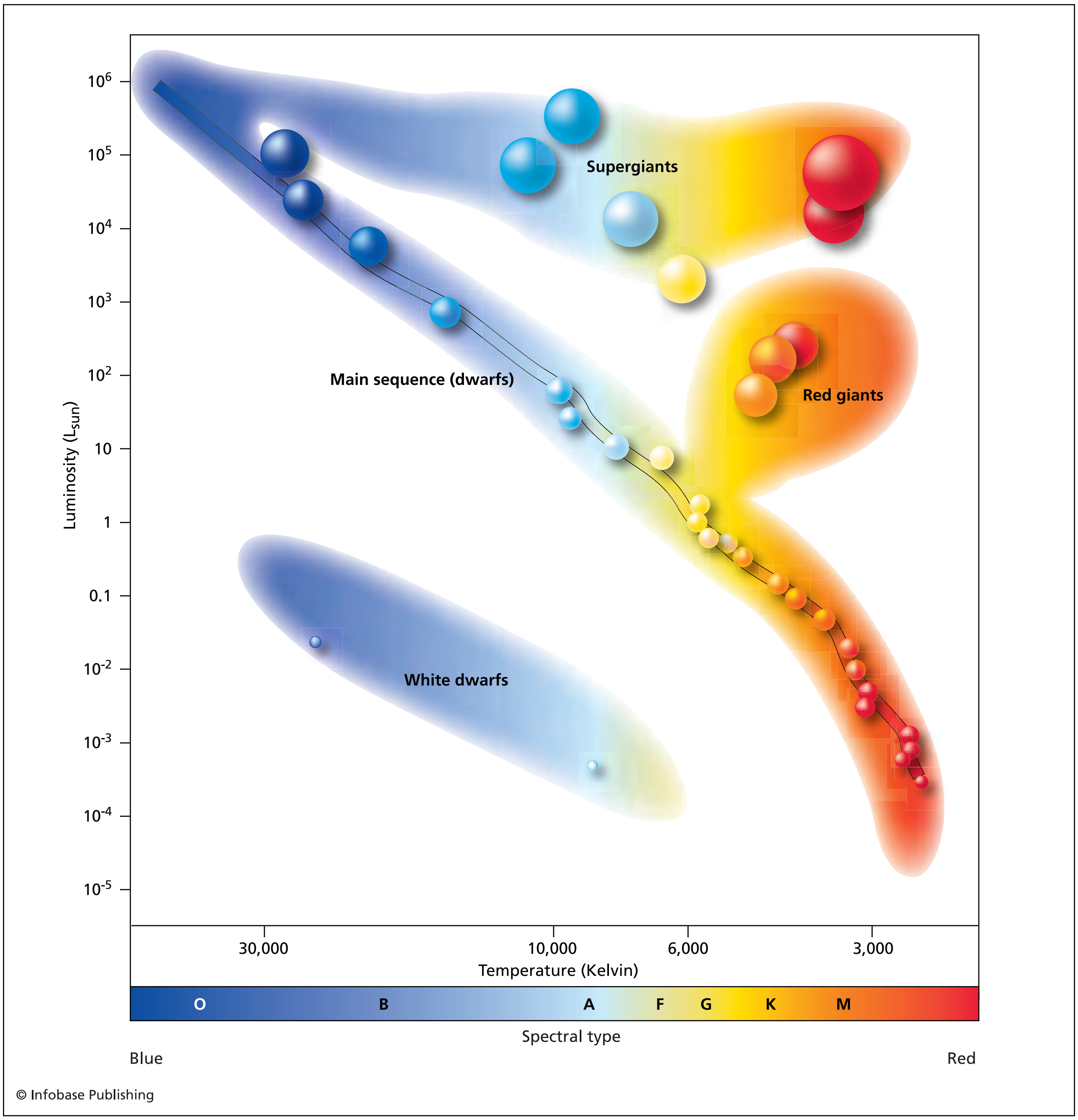
Interstellar Cloud

Stars that are close to a solar mass start their evolution as an ordinary, dense, and cold interstellar cloud that may be tens of parsecs across (1 parsec equals 3.3 light years), having temperatures of about 10 K, and densities of around 10^9 particles per cubic meter. The amount of mass in these types of interstellar clouds may be thousands or millions of times a solar mass at this stage. Typical giant molecular clouds that collapse to form solar-type stars are 6,000,000 solar masses and 100 light years across. Something must happen to this interstellar cloud to make it collapse and break into smaller pieces, but the exact mechanisms that trigger such a collapse are poorly known. There may be external triggers, such as pressure waves from nearby events (such as supernovas), gravitational collapse of smaller gas pockets in the interstellar cloud, or interactions of the magnetic fields and ionized particles. Once collapse begins the molecular cloud tends to fragment into tens to thousands of smaller and smaller clumps of matter, controlled by the gravitational instabilities within the nebula. Each of these clumps can then eventually develop into a star, with individual interstellar clouds thus capable of producing tens to thousands of new stars. Collapse from a stable interstellar molecular cloud to a group of collapsing cloud fragments may take only a couple of million years. Examples of various stages of collapse of interstellar molecular clouds are abundant in the universe and include spectacular glowing clouds such as the emission nebula M20 that shows bright red dust clouds, dark regions, and young glowing protostars.

Collapsing Interstellar Cloud Fragment

As the huge interstellar cloud collapses into many fragments, it is useful to consider the processes inside one of the individual cloud fragments as it continues to develop into a star. Most of these fragments are about one to two solar masses but can be about 100 times the size of the Earth's present solar system. The temperature of the cloud is about the same as when it started to condense, but it would have an increased density of about 10^{12} particles per cubic meter in the center of the cloud fragment. The temperature has not changed because the density of the cloud is still too low to capture photons emitted from the gas, and the energy of the photons escapes to space instead of being absorbed by the cloud. However the very center of the cloud may experience significant warming by this stage, perhaps to 100 K, as the gas is denser there and can absorb more of the radiation produced in the gas. As the cloud continues to shrink, it becomes denser so that eventually the cloud begins to trap the radiation across large regions, and the temperature of the whole cloud increases. This causes an increase in the internal pressure (equated with temperature and speed of particle movement), which grows strong enough to overcome the force of gravity that was pulling the cloud together. At this stage, the contraction of the cloud stops and the fragmentation of the original cloud stops. The Orion nebula, in the constellation Orion, provides beautiful examples of cloud fragments that are lit by the absorption of radiation produced in the cloud.

The time from initial contraction to the end of fragmentation of the interstellar cloud may take only



Hertzsprung-Russell diagram showing stellar evolution. The diagram plots luminosity on the vertical axis and surface temperature or spectral class on the horizontal axis.

a few tens of thousands of years, and by this stage the size of the cloud fragment is roughly the same as Earth's present solar system, but the central temperature of the cloud has now reached about 10,000 K, while the peripheral temperatures at the edge of the cloud are still close to their starting temperatures. Since the edges of the cloud are cooler than the denser interior, they are also thinner, and the cloud takes on the shape of a thick ball in the center surrounded by a flattened and outward thinning disk. The central density in this stage may be 10^{18} particles per cubic meter.

The center of the collapsed fragment is now roughly spherical, dense, and hot and begins to resemble an embryonic protostar, as it continues to grow in mass as gravity attracts more material into its core, although the size of the internal embryonic protostar continues to shrink since the force of gravity in the core remains greater than the internal pressure generated by the gas temperature. At this stage

Infrared and visible light composite of Orion Nebula, 1,500 light-years from Earth, taken by *Spitzer* and *Hubble Space Telescopes*, November 7, 2006. The image shows a region of star birth, including four massive stars at the center of the cloud, occupying the region that resembles a yellow smudge near the center of the image. Swirls of green reveal hydrogen and sulfur gas that is heated and ionized by the intense ultraviolet radiation from the massive young stars at the center of the cloud. The wisps of red and orange are carbon-rich organic molecules in the cloud. The orange-yellow dots scattered throughout the cloud are infant stars embedded in a cocoon of dust and gas. The ridges and cavities in the cloud were formed by winds emanating from the four super massive stars at the center of the cloud. *(NASA Jet Propulsion Laboratory)*

the embryonic protostar develops a protosphere, a surface below which the material is opaque to the radiation it emits.

Protostar

The protostar in the center of the collapsed disk continues to shrink and grow in density, its internal temperature increases, and the surface temperature on its protosphere continues to rise, generating higher pressures. About 100,000 years after the initial fragment formed from the interstellar cloud, the center of the protostar reaches about 100,000,000 K, and free electrons and protons swirl around at hundreds of miles (km) per second, but temperatures remain below the critical value (10^7 K) necessary to start nuclear fusion to burn hydrogen into helium. The protosphere has a temperature of a few thousand K, and the radius of the protosphere places it at about the distance of Mercury from the Sun.

At this stage the protostar can be plotted on an H-R diagram, where it would have a radius of 100 or more times that of the present Sun, a temperature of about half of the Sun's present temperature, and a luminosity that is several thousand times that of the Sun. The luminosity is so high because of the large size of the protostar, even though the temperature is lower than the present temperature of the Sun. The energy source for the luminosity and elevated temperatures in this protostar is from the release of gravitational potential energy during collapse of the interstellar cloud.

Pressures build up inside the protostar at this stage from the elevated temperatures, but the gravitational force is still stronger than the thermal pressures, so contraction continues albeit at a slower rate. Heat diffuses from the core of the protostar to the surface, where it is radiated into space, limiting the rise in temperature but allowing contraction to continue. If this did not happen then the temperatures would rise in the star and it would not contract enough to reach densities at which nuclear fusion would begin, and it would not form into a true star, but would remain a dim protostar.

The protostar continues to move down on the evolutionary H-R diagram toward higher temperature and lower luminosity as the surface area shrinks. Internal densities and temperatures increase while the surface temperature remains about the same,

Horsehead Nebula in the Orion molecular cloud complex. This image was produced from three images obtained with multimode FORS2 instrument at the second VLT Unit Telescope. *(European Southern Observatory)* but the surface can be intensely active and be associated with intense solar winds such as those that characterize T-Tauri stars. A possible example of a protostar in this stage of evolution in the Orion molecular cloud is known as the Kleinmann-Low Nebula, which emits strong infrared electromagnetic radiation at about 1,000 times the solar luminosity. Some protostars are surrounded by dense dark dust clouds that absorb most of the ultraviolet radiation emitted by the protostars. This dust then reemits the radiation at infrared wavelengths, where it appears as bright objects. Since the source of the radiation is cloaked in a blanket of dust, these types of structures have become known as cocoon nebula.

By the time the protostar has shrunk to about 10 times the size of the Sun, the surface temperature is about 4,000 K and its luminosity is now about 10 times that of the Sun. However, the central temperature has risen to about 5,000,000 K, which is enough to completely ionize all the gas in the core but not high enough to start nuclear fusion. The high pressures cause the gravitational contraction to slow, with the rate of continued contraction controlled by the rate at which the heat can be transported to the surface and radiated away from the protosphere. Strong presolar winds at this stage blow hydrogen and carbon monoxide molecules away from the protostar at velocities of 60 miles per second (100 km/sec). These winds encounter less resistance in a direction that is perpendicular to the plane of the disk formed from the flattened interstellar cloud fragment, since there is less dust in these directions. In this stage, therefore, some protostar nebulae exhibit a strong bipolar flow structure, in which strong winds blow jets of matter out in the two directions perpendicular to the plane of the disk. This strange-looking structure eventually decays, though, as the strong winds blow the dust cloud away in all directions.

Approximately 10 million years after becoming a protostar, when the temperature reaches about 10,000,000 K and the radius about 6,200 miles (10,000 km), nuclear fusion begins in the center of the protostar. At this stage, a true star is born and is typically a little larger than our present Sun, the surface temperature is about 4,500 K, and the luminosity is about two-thirds that of the present Sun.

Main Sequence Star

The newly formed star continues to contract for about another 30 million years after nuclear fusion has begun; the central density increases to 10^{32} particles per cubic meter, the central temperatures rise to 15,000,000 K, and the surface heats to about 6,000 K. At this stage the thermal pressures balance the gravitational contraction forces, and the rate that nuclear energy is generated in the core equals that at which it is radiated at the surface. At this stage the star has reached the main sequence, where it can burn stably for about another 10 billion years without significantly changing.

VARIATIONS IN STELLAR FORMATION WITH SOLAR MASS

The sequence of star formation described above is based on the evolutionary history of a one-solar-mass star from the interstellar cloud to main sequence stages. Stars with larger sizes form from initial interstellar molecular cloud fragments that condense into larger fragments, and smaller stars form from smaller fragments. Each of the stages for larger or smaller stars may be similar to the stages described above, but the magnitudes for size, density, temperature, and time for reaching different stages can vary significantly for stars of different mass. Larger mass embryonic stars generally have higher luminosities, densities, and surface temperatures at different stages compared to the lower-mass objects, and they move along the evolutionary paths much faster than smaller-mass objects. The most massive stars can progress from the interstellar cloud stage to being a main sequence star in only a million years, compared to 50 million years for stars with only one solar mass. At the other end of the spectrum, stars with lower masses are cooler, smaller, and can take much longer to evolve into main sequence stars, even a billion years or more in cases.

The zero-age main sequence for a star is the time at which the stellar properties become stable and the star enters a steady period of burning or fusion. This is the time the star is effectively born or joins the main sequence. Stars do not evolve along the main sequence trend on the H-R diagram; rather the main sequence is just the point at which most stars stop evolving for an extended period of time and show a stable relationship between luminosity, temperature, and star mass. Higher mass stars plot on the upper left part of the H-R diagram; lower mass stars plot in the lower right.

Some cloud fragments are too small to ever produce a star but end up producing other gaseous bodies in the universe. The giant gaseous planets of Jupiter and Saturn are examples of parts of condensed interstellar clouds that formed from parts of the cloud that were too small to produce a star. These planets collapsed from the interstellar cloud like the Sun but were too small to continue contracting to produce a star or to start nuclear fusion. Other interstellar cloud fragments that are too small to produce stars become isolated in space as fragments of unburned cool matter. These objects may be abundant in interstellar space but are difficult to detect since they are small and cold. They are called brown dwarfs and may account for much of the unknown mass in the universe.

EMISSION NEBULAE

The sections above focused on the formation of stars from the collapse of interstellar dust clouds but did not focus on the effects these processes have on the surrounding intergalactic medium.

Star formation as described above does not usually result in the formation of just one star, but rather a group or cluster of stars with similar characteristics and ages in a region that represents the original collapsed interstellar cloud. The more massive the original collapsed dust cloud, the more new stars that form. Dispersed within this region is a variable amount of unused gas and dust that did not make it into the newly formed stars or associated planetary systems. This gas is commonly ionized by high-energy photons and glows in different colors as an emission nebula.

Observations of newly formed star regions and star clusters show that low-mass stars form more commonly than high-mass stars, but at present astronomers do not understand the reasons that control the types and spacing of stars, nor why in some cases the process is very efficient and uses much of the original dust and gas from the collapsed dust cloud, whereas in other cases the process is not efficient.

If very massive stars form they have such strong winds and radiation that they typically blow away all the gas from the surrounding nebula, revealing the brightly glowing new star clusters that formed from the collapse of the nebula. Such star clusters have also been detected in collapsed nebulae without such large stars in them, but dust that absorbs the ultraviolet radiation surrounds them, so they can be detected only with infrared observations. Analysis using data from infrared observatories of the collapsed dust clouds in the Orion Nebula clearly show many areas where there are star clusters hidden optically by the emission nebula but shining brightly and identifiable in infrared images. Astronomical observations show that in these regions, for every large star that forms there may be tens to hundreds of smaller stars in the same region. Typical emission nebula may be 10 parsecs (33 light years) across and contain roughly 1,000 new stars formed during the collapse of the interplanetary dust cloud. Other star clusters seem to form in a more dispersed way, spanning greater distances but having an order of magnitude fewer (about 100) stars; these are referred to as star associations.

Over time stars from these clusters and associations interact. Gravitational forces between the stars tend to eject the lighter stars out of the clusters, and the clusters eventually degenerate into individual stars that are not associated with large clusters. Most of the young clusters observed in emission nebulae last a few hundred million years before they are dispersed, but some of the larger clusters may last a few billion years.

See also ASTRONOMY; ASTROPHYSICS; CONSTELLATION; COSMOLOGY; DWARFS (STARS); GALAXIES; INTERSTELLAR MEDIUM; STAR FORMATION; STELLAR EVOLUTION.

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stellar evolution During their lifetime, stars undergo a predictable sequence of changes that are a function of their mass. The lifetimes of individual stars range from a few millions of years for the most massive stars to trillions of years for less massive stars. Some stars have lifetimes longer than the age of the universe. To understand stellar evolution astronomers and astrophysicists study large numbers of stars at different stages in their evolutionary history and integrate these observations with computer models that simulate stellar evolution and structure. Stars change dramatically during their formation stages until they reach the main sequence, when they burn uniformly for about 90 percent of their history. As the nuclear hydrogen fuel runs out near the end of a star's history, it may once again undergo dramatic changes as it leaves the main sequence. The path a star takes near the end of its life depends primarily on its mass and somewhat less on its interactions with other nearby stars. The end states of stars can be extremely spectacular and strange, or they can just fade away from visible detection.

THE MAIN SEQUENCE

After stars form over a period of a few to a few tens of millions of years, they reach a steady state of hydrogen burning that can last for 10 billion years or more before changing significantly again. Stars on the main sequence plot on a fuzzy line on a diagram

Hubble image of bright blue newly formed stars that are blowing a cavity in the center of star-forming region N90 *(NASA)*

depicting the relationship between solar luminosity and surface temperature (called a Hertzsprung-Russell or H-R diagram [see page 698]), indicating a balance between a star's temperature, luminosity, and mass during the hydrogen-burning stage. Once a star uses up its hydrogen fuel, these relationships change, the star is out of equilibrium, and it leaves the main sequence, plotting in different places on the H-R diagram, depending on its mass. The time that a star leaves the main sequence represents the beginning of its end, and its lifetime after departure from the main sequence will be relatively short.

Low-mass stars burn so slowly that most still exist, as they have not yet exhausted their hydrogen fuel supply. In contrast high-mass stars burn more quickly; some of the largest stars stayed on the main sequence for only a few tens of millions of years. Most of the very massive stars that were created in the history of the universe have left the main sequence, gone through their death throes, and moved to the end states of existence. Stars of intermediate mass are experiencing or will experience intermediate fates. In general low-mass stars have a gentle end of their existence as bright objects, whereas high-mass stars generally have an explosive ending. The exact boundary between high- and low-mass is fuzzy but ranges somewhere between five and ten solar masses.

While a star is burning hydrogen on the main sequence, it maintains a balance or equilibrium between gravitational forces that tend to draw all the atoms together to the center of the star and gas pressure from the hydrogen burning inside the star pressing outward against gravity. This equilibrium is maintained for about 90 percent of a star's lifetime, and as long as it is maintained nothing spectacular will happen to the star; it will simply continue to burn hydrogen in fusion reactions, converting it into helium. The nuclear fusion process is a multistep process in which four hydrogen nuclei (protons) combine to produce one helium 4 nucleus, emitting gamma ray radiation and two neutrinos. Over this time period the star surface may occasionally erupt, forming giant solar flares or sunspots, and is constantly emitting large amounts of photons and other particles from the nuclear reactions inside. A star typically grows in luminosity during its history on the main sequence. The Earth's Sun, for instance, is now about 30 percent more luminous than when the Earth, Sun, and solar system formed nearly 5 billion years ago.

FUEL SHORTAGE STAGE

After about 10 billion years, a star the size of the Earth's Sun will start to run out of hydrogen fuel in its central core, in a gradual process that has a catastrophic ending. The core of the star initially is composed of mostly hydrogen and about 10 percent helium, but the amount of helium gradually increases over billions of years until at about 10 billion years the core consists of all helium. Outer parts of the star will still contain large amounts of hydrogen at this stage, but the critical, high-temperature, high-pressure core has at this stage depleted its hydrogen fuel supply. The reason some hydrogen remains in the outer parts of the star is that the temperatures are lower in those regions, and the hydrogen burning proceeded at a lower rate than in the core. At this stage, the inner core stops burning hydrogen, and the main area of fusion reactions moves higher (farther from the star center) in the star interior. With time the inner core of non-burning helium grows. This leads to an imbalance between the forces of gravity and gas pressure in the inner core, because the lack of hydrogen burning in the inner core decreases the gas pressures in that region, while the gravity remains the same. Eventually, the force imbalance grows to the point that something serious must happen.

CORE CONTRACTION AND HYDROGEN SHELL BURNING

As the helium in the core builds up it cannot burn, since it requires much higher temperatures to fuse than does hydrogen. The result is that when the hydrogen is used up, the core contracts, since the gas pressure without high temperatures from nuclear fusion is not sufficient to counteract the force of gravity. The shrinkage of the core then releases gravitational potential energy that creates heat, raising the temperature of the core. As the core grows increasingly hot in this way (but not hot enough to burn helium), it raises the temperatures of the outer parts of the star where there is still abundant hydrogen, causing this hydrogen to burn much faster than before. The hydrogen burns especially fast around the non-burning helium core, forming a hot-burning shell within the interior of the star. This is called the hydrogen shell–burning stage. The burning of the hydrogen in this shell generates more energy faster than when the star entered onto the main sequence, and the star begins to significantly increase in luminosity.

As the hydrogen shell burning continues, the star begins to leave the main sequence and is no longer in equilibrium. The helium core is shrinking and becoming hotter, nearing temperatures sufficient for helium burning. The hydrogen shell burns faster, increasing the gas pressures and temperatures in the outer parts of the core and causing the outer parts of the star to expand in response, which lowers temperatures on the surface.

The overall consequences of this phase of star evolution, then, are that the core shrinks and heats up, while the outer surface expands dramatically, becomes more luminous, and cools by about 2,000 K, over a period of about 100 million years. The luminosity of the star continues to rise as the temperature falls and the radius of the star increases to about 70 times that of the initial, one-solar-radius star. At this stage the one-solar-mass main sequence star has become a red giant.

RED GIANTS

Red giants are huge stars, roughly 70 times as large as the Earth's Sun, yet with a helium core only a few times larger than the Earth, or about 1/10,000 the size of the star. With the lack of nuclear fusion in the core, the gas pressures allow gravitational forces to compress the helium to high densities, such that about 25 percent of the star's mass exists within the core, and the density rises to about 1,000,000,000 kg per cubic meter. Strong stellar winds in this stage blow away a significant part of the star's mass, typically 20–30 percent of the original mass.

HELIUM FUSION STAGE

The core of the red giant continues to contract while the outer layers of the star continue to expand for a couple hundred million years after the star leaves the main sequence. This would lead to the destruction of the star with the core collapsing and expelling the outer shells of the planet to space, but before that happens the temperatures in the core rise above the 100,000,000 K required to start burning helium. When this temperature is reached helium fusion begins, and the dense hot core starts burning the helium, causing it to fuse to form carbon and releasing tremendous energy and heat in the process.

By the time the helium burning begins in the core of the red giant star, pressures have risen so high that a new state of matter, called electron degenerate matter, exists in the star's center. Pressures have squeezed the free electrons so close together that they cannot be physically compressed further and have degenerated to a low energy quantum level in which they cannot accommodate the addition of more heat. The result of the onset of helium fusion in this electron degenerate matter is therefore unstable. The gas pressure in the electron degenerate matter cannot rise because the electrons cannot be pushed farther apart; instead, the new energy added to the system by nuclear fusion causes it to undergo a rapid acceleration of the helium burning, causing a massive explosive reaction called the helium flash. This uncontrolled helium burning lasts only a few hours, but releases enough energy to expand the core, lowering its density out of the range of the electron degenerate matter quantum state to a condition where gas pressures in the core can build up to equalize the inward pull of gravity, and the core stabilizes.

After the helium flash, the red giant changes its evolutionary path on the H-R diagram. It stops expanding and becoming more luminous, reversing its direction to become less luminous with a higher surface temperature, and will then reside on a different branch of the H-R diagram known as the horizontal branch, where stars plot for the time period that they burn helium stably in their cores. The position the star plots in this horizontal field depends on how much of the star's mass remains after the strong solar winds from the red giant stage blow away large parts of the mass. Stars in the helium-burning stage lie on a horizontal line because they are all characterized by a similar luminosity, although stars with higher masses have lower surface temperatures in this stage.

Helium burning proceeds very rapidly in the core of the star after the helium flash, producing carbon that builds up as a carbon ash shell in the core. The high temperatures in the core help the helium to burn very quickly toward depletion, using up the helium fuel within a few tens of millions of years after the helium flash. The carbon in the core builds up and shrinks, releasing gravitational potential energy and heating up as it shrinks, and the helium fuel is progressively used up. This higher temperature causes more rapid burning of helium in a shell around the core, which is then progressively surrounded by a hydrogen-burning shell and a non-burning shell beneath the star's surface. The high temperatures in this stage cause the non-burning shell to expand, once again becoming a huge red giant, this time burning helium in its core. The helium burning proceeds much more rapidly than the hydrogen burning that occurred when the star first became a red giant, and the star moves up a different path on the H-R diagram called the asymptotic giant branch. The much higher luminosity and radius in this stage classify the star as a red supergiant. The carbon core continues to shrink, while the helium- and hydrogen-burning shells move progressively outward and reach higher temperatures and luminosities. This intense, furious burning marks the beginning of the end for the star; its death is near.

STAR DEATH: PLANETARY NEBULAE

For stars with masses approximately equal to that of the Earth's Sun, the period of expansion of the shell and core shrinkage will continue, but the gravitational contraction will not release enough energy to reach the 600 million K needed to start nuclear fusion of carbon. Densities in the core continue to increase until about 10,000,000,000 kg per cubic meter, when the carbon ash in the core attains an electron degenerate state and can be compressed no further. At this stage temperatures stop rising, since there is no internal nuclear fusion and gravitation contraction has stopped, so no more potential energy is released. Thus, when the helium fuel is all burned, the fires go out.

When all the helium is used from the core and just a dense carbon ash remains, the core of the star is essentially dead. The inner core continues to accumulate the spent carbon while outer core layers form shells that burn helium and hydrogen at an intense pace and the outermost part of the star continues to expand. The intense burning in the helium shell is very unstable in this stage, and stars typically experience a series of helium shell flashes from the fluctuating temperatures at high pressures. These helium flashes send intense radiation waves to the star's surface, causing it to violently pulsate. Expansion of the outer layers of the star causes the temperature of the outer layers to drop, which has the effect of allowing electrons that were dissociated by the earlier higher temperatures to recombine with atoms, releasing additional photons in the process. The energy from these photons causes the outer envelope of the star to move progressively further from the core of the star, causing the radius to oscillate in progressively larger variations in distance from the core. This process causes the outer layers of the star to be ejected to space at tens of miles (km) per second.

The wild oscillations of the star and ejection of material from the outer layers forms a new highly unusual looking stellar structure called a planetary nebula. This nebula has a small, dense core made of the spent carbon ash with a shell of material still burning helium into carbon. A span of relatively empty space about the size of Earth's solar system surrounds the core, succeeded outward by a glowing ring consisting of the ejected outer layers of the former giant star. The Milky Way Galaxy contains more than 1,000 known planetary nebulae, which last only for a very brief period of stellar evolution, typically a few tens of thousands of years as compared to the billions of years of the star's previous life history. The planetary nebula stage marks the death, or the final active stage of the star, so the thousand or so planetary nebula known from the Milky Way represent the stars currently (when the light was emitted) going through their death throes. When stars die, however, they do not go away, they simply disappear from sight. As the dead stars fade from view they go through two more stages, the white dwarf and the black dwarf stages.

WHITE DWARF STAGE

Over a relatively short period of time, tens of thousands of years, the expanding shell of material on the outer parts of the planetary nebula disperses into interstellar space and fades away as a visible nebula. The atoms of hydrogen, helium, and a small amount of carbon are in this way added to the interstellar medium, having spent the past few billions of years in the interior of a star.

The carbon core of the dead star, however, continues to go through a few more stages of evolution or degeneration. After ejection of the outer layers of the former red giant star, the remnant core, which is about the size of the Earth, glows white-hot, giving the name white dwarf. The initial surface temperature of the white dwarf is about 50,000 K, but the heat is only heat stored from its formerly active processes of nuclear fusion and gravitational collapse; no new heat is generated in the white dwarf. White dwarfs can be extremely dense, however; for example, Sirius B is about a million times denser than Earth. With time this core of a formerly great red giant will continue to cool, fade, and become a virtually invisible black dwarf.

BLACK DWARF STAGE

As the white dwarf continues to cool, its surface becomes less and less luminous until it becomes a cold, dark, carbon-rich, burned-out sphere floating in space. Even as it cools, the black dwarf no longer contracts. This is because its atoms are so dense that they are in the electron degenerate state and cannot be squeezed together any further. Therefore most solar-sized stars end up as dense, cold, dark, Earth-sized objects, perpetually cooling in space. Such is the fate of most solar-sized stars—to cool to near 0 K and float invisibly in space, waiting for some chance encounter with another star, black hole, or object that could possibly give its atoms a new life.

EVOLUTION OF HIGH-MASS STARS

Stars that have much higher masses than the Earth's Sun evolve faster than the typical scenario for a one-solar-mass stellar evolution outlined in this entry. The evolutionary speed is particularly dramatic for the nuclear fusion stage, since these stars burn their fuel supply at a much higher rate than solar-size stars. For instance, whereas a Sun-type star will typically spend about 10 billion years in the hydrogen-burning stage on the main sequence, a five-solar-mass star will spend only a few hundred million years in this stage.

After the hydrogen-burning stage is complete, high-mass stars also leave the main sequence and burn helium, albeit at a higher rate than their lower-mass cousins. However, since high-mass stars enter the helium-burning stage with lower internal densities than their lower-mass equivalents, electron degeneracy has not been attained in the core, and the star can burn helium smoothly and without the helium flashes that characterized the low- or normal-mass stars. Another difference is that since the core of a high-mass star can continue to contract after burning helium, it can attain temperatures high enough to start burning carbon (600 million K), and the high-mass star does not therefore enter a white dwarf stage. Instead, it continues to burn heavier and heavier elements, fusing hydrogen to helium, helium to carbon, carbon to oxygen, oxygen to neon, neon to magnesium, magnesium to silicon, and silicon to iron. As the star burns different fuels, its radius expands and contracts and its surface temperature goes up and down multiple times, instead of the simpler history of low-mass stars. The fusion reactions proceed at faster and faster rates as the star burns heavier elements, as if some catastrophic event is approaching. The fate of high-mass stars is an explosive ending, as the accelerating reactions and burning lead to one of the universe's most spectacular events, that of a supernova, or stellar explosion.

See also ASTRONOMY; ASTROPHYSICS; BINARY STAR SYSTEMS; CONSTELLATION; COSMOLOGY; DWARFS (STARS); GALAXIES; INTERSTELLAR MEDIUM; PLANETARY NEBULA; STAR FORMATION; SUPERNOVA.

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Steno, Nicolaus (1638–1686) Danish *Anatomist, Bishop, Geologist, Paleontologist* Nicolaus Steno is probably the first scientist to clearly show that fossils are organic remains of formerly living organisms. He studied anatomy at Copenhagen and Leiden, and Florence. While dissecting a shark, he noted the similarity between the teeth of the modern shark and fossil shark teeth in local strata. After this revelation, Steno traveled around Tuscany collecting as many fossils as he could, becoming obsessed with understanding the origin of fossils. He produced a major work on the origin of fossils, the *Prodromus*, in 1669, that led him to ponder differences between his observations and the history of the world as described in his version of the Bible. Steno proposed the law of stratal superposition, clearly outlining that younger rocks are deposited over older rocks, and he recognized a sequence of changing fossil forms in the stratigraphic record. He also described metalliferous mineral deposits, recognizing crosscutting veins, and he described volcanic mountain building, erosion, and faulting. Nicolaus Steno is considered the father of geology for formulating three major principles in a single geological work: the law of superposition, the principle of original horizontality, and the principle of lateral continuity.

EARLY YEARS

Niels Stensen was born on January 1, 1638, to Sten Pedersen and Anne Nielsdatter in Copenhagen, Denmark. Sten was a skilled goldsmith, and one of his regular customers was the Danish king. Niels suffered from an unknown illness from the age of three to six. As he recovered, his father died, leaving the family without a source of income. Anne remarried quickly, but her new husband died the following year. She did marry again, but Niels's childhood was quite unstable, foreshadowing the rest of his life. In addition, the mid-1600s was a rough period for Denmark. The Thirty Years' War had ravaged Europe since its inception in 1618. Between 1654 and 1655, the plague stole the lives of one-third of the Danish population.

In the midst of all this, Niels received an education. He attended the Lutheran academy Vor Frue

Skole, which lost half its student population to the plague. As was common for educated people at the time, his name was Latinized to Nicolai Stenosis, which has since been altered to Nicolaus Steno. Ole Borch taught Steno Latin at Vor Frue, but Borch was interested in many subjects and was an admired physician as well. He is credited with pointing Steno toward science. He performed many scientific demonstrations that impressed Steno. The two men developed a friendship based on a common love of natural and experimental philosophy.

Steno entered the University of Copenhagen in 1656 to study medicine. It was an unfortunate time to attend college, as the country went to war with Sweden. Food and fuel were in short supply on campus. Many professors and fellow students had joined the war effort, leaving few students behind who essentially had to teach themselves. This was not a problem for Steno, who read voraciously. During this time, he kept a journal titled *Chaos*. Much of what is known about Steno's studies, inner struggles, personal characteristics, and reflections on literature were recorded in this journal.

THE SEASHELL QUESTION

Thomas Bartholin, an anatomy professor from the University of Copenhagen, was famous for his discovery of the vessels that carry lymph throughout the body. Lymph is a transparent, yellowish fluid that plays an important role in the immune system and in the transportation of certain materials throughout the body. Bartholin not only conveyed an appreciation for anatomy to Steno but introduced the famous seashell question to him.

In mountainous regions, objects which resembled seashells and other marine life-forms were found embedded in the rock of the mountains. Though their shape resembled that of marine life, their composition was of a different material, more similar to hardened rock than brittle shells. Did they grow naturally out of the Earth itself? Or might they be remains of past marine life? One thing on which Catholics and Protestants did agree was the creation of the Earth and all life by an omnipotent God, but land and water were separated on the third day of creation, whereas fowl and water life were created on the fifth day. So, if the fossils were the remains of past marine life, how did they get to be embedded in dry land? (At the time the word *fossil* referred to anything that came from the Earth.) One possible explanation was the great flood described in Genesis. However, given the short period the entire Earth was covered by water, there was not enough time for slow clams to travel the distance to the remote locations where the fossils were sometimes found. Besides, they were made of a different material. The arguments went back and forth. This paradox bothered some more than others. Steno listened to Bartholin's debate with intrigue and recorded several notes about fossils in his *Chaos* journal; nonetheless, he continued with his medical studies. He was particularly interested in anatomy.

Steno originally had wanted to study mathematics, but medicine offered better prospects for a career. Anatomy seemed very clear and logical to Steno. Perhaps it appeased his mathematical yearnings. After three years at Copenhagen, Steno left for the Netherlands in possession of a letter of introduction from Bartholin. He stopped by Amsterdam and was hosted by a physician friend of Bartholin, Gerhard Bläes. In Amsterdam, Bläes gave Steno private anatomy lessons.

DISCOVERY OF A SALIVARY DUCT

During his studies Steno was examining the arteries and veins surrounding the jaws on a butchered sheep head and inserted his skinny metal probe through a small tunnel and heard a clinking noise from hitting teeth. After close examination, he realized he had discovered a previously unrecognized duct leading from the parotid gland to the oral cavity. The parotid glands supply saliva to the mouth. He pointed this out to his teacher. Bläes immediately cast off Steno's finding as a blunder. He thought Steno must have clumsily probed through the side of the cheek accidentally, but Steno had faith in his own dissecting skills. When he demonstrated to Bläes that he did not puncture the cheek, Bläes then retorted that it must be a deformity.

After staying in Amsterdam for three months, Steno made his way on to Leiden where he enrolled at the University of Leiden in 1660. He repeated his dissection to his new professors who excitedly accepted the duct as a new and real discovery. They presented his findings. Word got back to Amsterdam, and Bläes angrily responded by corresponding that it was his own discovery and that Steno had stolen credit. Bläes rushed to publish his account of the newly discovered duct. This drove Steno to work even harder to prove his skills as an anatomist. He continued his dissection studies and, in 1662, published *Anatomical Observations on Glands,* in which he described not only the parotids but all of the glands in the head. He built up a highly regarded reputation and was able to reveal the inaccuracies of Bläes's phony report by providing a description that only an extremely skilled anatomist could give. The duct leading from the parotid to the oral cavity is referred to today as Stensen's duct, *ductus stenosis.*

When his stepfather died in 1663, Steno briefly returned to Copenhagen. In 1664 he published the results of his years of research at Leiden, *On Muscles and Glands*. That same year Steno was awarded a doctorate of medicine from the University of Leiden in absentia. He was hopeful of obtaining a position at the University of Copenhagen but was rejected. Thus he set out again, landing in Paris for a year.

QUESTIONING DESCARTES

Steno believed the best way to learn was to study the objects of interest directly. For example, to understand poetry one should not simply read one scholar's interpretations of a verse, but he should read the verse himself. If one was curious about botany, she should observe plants, not only rely on pictures in books. Though Steno was well read, he did not believe books were the utmost authority. Proof was necessary for progress. The 17th-century French philosopher and mathematician René Descartes had popularized the method of systematically doubting everything at first. Direct observation or other reliable proof was necessary in order to attain absolute certainty. The young Dane subscribed to this new philosophy.

By 1665 Steno was engrossed in the anatomy of the brain. Though much had been written about the structure and function of the brain, Steno confessed at a public lecture in Paris to knowing nothing about the brain. After shocking the audience by making such a bold declaration, the prominent anatomist proceeded to explain his philosophy on learning. He said he was starting from scratch. Rather than relying on the many varied, written descriptions from centuries of so-called anatomists who had mangled brains and followed only prescribed methods of dissection, he planned to explore it carefully on his own. He would accept only that which he directly observed. His presentation, *Discourse on the Anatomy of the Brain,* is remembered for his scientific philosophy as well as the content itself.

Steno had been initially introduced to Cartesian philosophy by Ole Borch. While Steno subscribed to Descartes's method of doubting first, he was very bothered by Descartes's lack of practicing what he preached. For example, the function of the heart had mystified physicians for centuries. The ancient Greek philosopher Aristotle believed the heart was responsible for a person's emotions and intelligence. In the second century Galen said the heart was the body's source of heat and that it was the seat of the soul. It prepared "vital spirits" that were transported around the body in the blood, giving life to the organism. Descartes said the heart was a furnace. When the blood passed through it, it became heated and expanded, and as a result, the blood rushed into the arteries. Back in Leiden, Steno had been intrigued by this and decided to investigate. He purchased an ox heart from the local butcher. He cooked the organ and carefully peeled away the outer protective layer, noticing fibers similar to those present in muscle tissue. The fibers were arranged in a manner such that contraction would force the blood out through the arteries. Having a rabbit on hand, he dissected its muscles to compare to the ox's heart. Not surprisingly, he found them to be essentially the same. He concluded that the heart was simply a muscle that worked to pump blood around the body. Sometimes things are as simple as they seem. Yet this instance troubled him, and he began losing faith in Cartesian philosophy. He brought these doubts with him from Amsterdam to Paris.

In *On Man,* Descartes claimed that the human body was simply a machine and that the pineal gland coordinated movements of the body in accordance with the feelings of the soul. He thought the pineal gland caused the actual moving by pulling strings like a puppeteer. It seemed that Descartes based an awful lot of assumptions either on some shoddy dissections or on the inaccurate records of others. In his Parisian brain dissections, Steno found the pineal gland to be completely stationary. There was no way it could perform the functions Descartes claimed. Cartesian anatomy seemed to be based on faulty deductive reasoning and conjecture rather than experimentation, something that bothered Steno extremely.

How could one accept Descartes's rational proof of the existence of God when Descartes could not even verify basic anatomical facts? From *Chaos,* it is known that Steno was always deeply religious, but this sequence of events caused him much spiritual anxiety. Nevertheless, he stood by the mechanical approach to science, even if Descartes had not. He became frustrated with Paris, where people did not want to hear him question the venerated Descartes. So he picked up and moved again.

STUDIES ON MUSCULAR CONTRACTION

In 1666 he arrived in Florence, Italy, by way of the Alps, where he was reminded of the seashell question. He was awed by the massive mountains and delighted to observe the rock strata firsthand. He was also pleased to find a group of similar-minded philosophers who thrived on experimental science. One of these men was Francesco Redi, the grand duke's physician. Redi had disproved spontaneous generation. People had thought that flies came to life from dung or rotting meat, but Redi showed that if the meat was covered with netting, then no flies appeared. Preexisting flies needed access to the organic matter to lay the eggs that developed into maggots. Redi was also a member of the Accademia del Cimento, a group devoted to experimental science. This group was sponsored by the grand duke of Tuscany, Ferdinando II de'Medici, and his brother Prince Leopoldo. The intelligent Medici brothers were not only formal philanthropists, but they actively participated in the experiments and the discussions of the Cimento. They generously provided materials for experiments and welcomed Steno into their association. The grand duke gave him an appointment as a physician at the Hospital of Santa Maria Nuova, leaving him plenty of time to pursue independent research.

Steno had been working on a new line of research involving muscle contraction. Anatomists believed that muscles moved because something pushed on them, yet muscles seemed to contract on their own. How did this happen? It certainly was not the pineal gland. One hypothesis was that fluids rushed in, causing the muscle to swell. With support from other members of the Cimento, Steno pursued this problem. Geometrically, he showed that when a muscle contracted, it neither grew nor shrank. The overall volume was maintained though the shape of the muscle fibers changed by contracting. These results were published in *Elements of Muscular Knowledge* in 1667.

GLOSSOPETRAE

While waiting for these results to be published in the fall of 1666, an enormous great white shark that weighed about 2,800 pounds (1,270 kg) was captured and killed on a beach off Livorno. Ferdinando asked Steno to dissect its head, which was brought to Florence. Before a large audience, Steno carefully dissected away the skin and soft tissues and examined the nerves and the tiny brain. The excitement at the scene must have been incredible. The beast's teeth were almost three inches (7.6 cm) long, and each jaw had 13 rows, but the shape of the teeth was what drew Steno's attention. They resembled a type of fossil about which he had first learned from Bartholin and had since viewed for himself. Glossopetrae, sometimes called tongue stones, were a type of hard, blackish, serrated, triangular stone. They were believed to have magical powers and were used to treat everything from speech impediments to poisoning. No one knew exactly where they came from. Some thought they were hardened woodpecker tongues. Others thought they fell from the heavens. They seemed abundant after heavy rain, so maybe they were jagged edges from lightning bolts. One explanation was biblical. The apostle Paul had been bitten by a poisonous snake on the island of Malta but was unaffected by the bite. The Maltese people thought Paul cursed the viper, making its venom harmless, and that nature honored this miracle by growing the glossopetrae in the shape of vipers' teeth. Steno thought they looked suspiciously similar to shark teeth.

He questioned all the stories he had heard and became obsessed with determining the nature of these glossopetrae. Steno was not the first to compare the tongue stones to shark teeth, but if they were shark teeth, how did they get onto dry land? And why was their composition different from live shark teeth? These questions reminded him of the seashell paradox. Actually, the marine bodies found in the Earth were often very near the glossopetrae. But the popular belief was that they came from the Earth itself. The Earth contained lapidifying juices (mineral-laden solutions) and unexplained "plastic forces" that gave form where none existed previously. People claimed that they could almost see rocks and other inanimate objects grow and multiply on pathways and in fields. The fact that some of the fossils resembled current marine creatures was just a trick of nature.

Steno began his examination. He compared glossopetrae side by side with shark teeth and found they were the same. Most of the arguments supporting the spontaneous growth theory were easily dismissed through logical reasoning. He described anatomical evidence supporting his belief. He explained that the chemical composition could change during fossilization though the shape would be preserved. He very cautiously worded his report to the grand duke, timidly stating that one would not be so far from the truth in saying the glossopetrae might be fossilized shark teeth.

Mentally he was engaged deep in the Earth following his preliminary studies and wanted to continue studying natural history. Just as the structure of body parts divulged their function, he believed the structure of the Earth also had something to say. Now he wondered not only how the seashell got on the mountaintop but also how did the mountain itself get there? Rather than rely on past speculation or biblical stories, he figured that studying the Earth was a good place to start finding certain truths about its own history. He was still deeply religious but began applying his critical thinking to his own religious beliefs. Whereas the Lutherans believed the Bible should be accepted literally, the Catholics were more lenient. After spending time observing the nature surrounding him, Steno had a hard time accepting that creation took place over only several days. What he observed from the Earth, its strata, the mountains, and the fossils told a different story.

The fact that the shapes of some fossils were true to the original forms of some current marine creatures told him that the shells must have been laid in a soft muddy layer that molded around the shell. Other subsequent events led to the hardening of the sediment while preserving the original shape. A solid became enclosed in another solid. He carried this further. Noting the ordered horizontal layering of the Earth's strata, he said that the layers must have resulted from sediment settling at the bottom of a liquid. The liquid evenly spread out across the surface, and the minerals and particles contained within the liquid fell heaviest first over the surface of the preceding layer. Each layer also spread out continuously over the Earth's surface, except where other large solid structures impeded the flow of the liquid. Furthermore, the layer underneath must have solidified before the upper layer hardened. This process occurred repeatedly, with each layer containing within it pieces of history from that geological age. Steno believed this took much longer than the 6,000 years that the Earth was believed to be in existence based on a biblical chronology. Scientists have since determined the Earth to be about 4.6 billion years old. Steno published some of his findings along with his shark head dissection report in 1667. The report was added as an addendum to his muscle paper, which was still at the printer from the previous fall.

A FORERUNNER

Impressed, the grand duke granted him a salary, and Steno became a full member of the Cimento. He was able to explore fully his new geological interests with all expenses paid. He traveled around Tuscany collecting fossils, climbing mountains, and examining strata. He also continued dabbling in anatomy and arrived at a startling conclusion during this time. It was obvious that females of many species of animals laid eggs, but Steno proved that females that gave birth to live organisms also produced eggs in their ovaries. This was important because people generally believed that the female only acted as an incubator for the seed that the man placed inside of her. However, most of Steno's time was spent deciphering the history of the Earth as told by its anatomy, that is, its distinct and unique geological formations.

Steno was thoroughly enjoying his scientific freedom and making remarkable progress. Unfortunately, in the fall of 1667 three events had a profound effect on the direction his life would soon take. First, Leopoldo was elected a cardinal and would no longer be able to manage the Cimento. Second, Steno received a letter from the king of Denmark requesting he return home and offering him a decent salary. Lastly, Steno converted to Catholicism. This would not please the Danish king, as Catholicism was banned in Denmark. Thus Steno wrote a letter to the king in reply explaining the new circumstance.

Previously, he would have been thrilled at being given such a position, but Denmark could not provide the rich geological material for his research that Italy could. He felt his new studies were coming to an end. He hastily continued observing shells and strata and crystals. By 1668 he started writing up his interpretations, *De solido intra solidum naturaliter contento dissertationis prodromus* (Forerunner to a dissertation on solids naturally enclosed in solids). This work is commonly referred to simply as *Prodromus,* Steno's magnum opus that earned him the title "founder of geology." The full dissertation never materialized, but *Prodromus* was packed full of clearly explained rational ideas, setting the framework for the new science of geology.

The principles outlined in *Prodromus* truly set the stage for all future geological studies. In attempting to address the central question of how a solid becomes enclosed in another solid, Steno revealed three chief geological principles. The law of superposition stated that the layers of strata in the Earth's crust represent a relative geological chronology. Each layer of sedimentary rock was older than the one above it and younger than the one below it. When a layer formed, all the matter on top of it was still fluid, and the layer below it was already hardened. The principle of original horizontality maintained that the layers of sediment were leveled after being deposited by water and, to a lesser effect, wind. If strata lie positioned at an angle, it was the result of a calamitous event that disrupted the crustal arrangement after the deposition. For example, a volcanic eruption or strong water current could cause a disturbance in an ordered stratigraphic sequence. The principle of lateral extension stated that strata were encompassed on all sides, or completely extended around the spherical Earth. Though these principles might seem quite simple today, Steno was the first to clearly state them. Steno also noticed that in crystal formation, the angles between the faces of the crystals were constant regardless of the shape or size of the crystal. This is referred to as the law of angle constancy.

In those days, books could not be published until they were approved by censors. The first *Prodromus* censor, Vincenzo Viviani, gave it a favorable recommendation. The second one, Redi, was more conservative and withheld it for several months. In the meantime, Steno received a reply from the king of Denmark granting him a position as royal anatomist in Copenhagen. A professorship was out of the question since he was now a Catholic. Steno left the arrangements for publication of *Prodromus* to Viviani and returned to Copenhagen for two years. They were not happy years. His research and his spirit suffered, prompting him to request a leave from the king so he could return to Florence, which he did in 1674.

FINAL YEARS

The new grand duke hired Steno to tutor his 11-year-old son. Then in 1675 Steno was ordained and took a vow of poverty. The pope appointed him a bishop in 1677. The last years of his life were fairly dismal.

In 1684 he wrote the pope, pleading for a release from his obligations. He wanted to return to Florence, where his days had been happiest. He was officially granted his request, but right before leaving he was asked to make a detour to help strengthen a new church in Schwerin. Unfortunately, the priest whom Steno was to be helping became ill, and Steno's brief delay in northern Germany was extended two years. Years of overwork, sleep deprivation, fasting, and not taking care of his physical needs took their toll, and Steno himself fell gravely ill. He died at age 48, on November 25, 1686, in Schwerin. His only belongings were a few worn-out garments.

Steno was not buried until 11 months later. His body was shipped from Hamburg to Florence in a crate that supposedly contained books. Seamen would have been hesitant to transport the crate if they had known its true contents. Steno's remains were buried in the crypt of the Medici in the San Lorenzo church. Steno's scientific career was brief, but his *Prodromus* is as relevant today as it was when it was published more than 300 years ago, and his ideas are presented in all current basic geology textbooks. In honor of the 300-year anniversary of the publication of *Prodromus,* in 1969 the Danish Geological Society started awarding a Steno Medal for outstanding achievements in the field of geology.

Steno's greatness was in clearly and formally stating that which seems simple and obvious, though it stirred up controversy at the time. People did not want to believe the heart, the seat of the soul, was simply a muscle. And what was fantastic about the organic material of sharks' teeth being replaced with mineral matter? Most upsetting, however, was Steno's insistence that scientists look to the Earth itself rather than supernatural revelation to learn about its creation. It took a frail Danish priest to open up the field of geology by reading a story that had been waiting to be told for billions of years.

See also EVOLUTION; FOSSIL; GONDWANA, GONDWANALAND.

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Stille, Wilhelm Hans (1876–1966) German *Tectonic Geologist* Wilhelm Hans Stille began his studies in stratigraphy and tectonics near his home in Hannover, Germany, and continued to do his fieldwork in this area for many years. His exploration work in Colombia introduced him to the continent of South America, where he continued to do most of his research later on. Although he did not do much research abroad, he helped other students who worked on the Mediterranean region. His constant reading helped him to become a leader in developing the field of global tectonics by synthesizing the geologic history of many regions. He is best known for proposing a system of about 50 orogenic phases in the Phanerozoic eon, many of which still bear the names he proposed. Stille used a concept known as geosynclinal theory that was later replaced by the plate tectonic paradigm. The basic idea of the discredited geosynclinal theory is that sediments accumulate in basins that cause the crust to sag downward, and when they become several miles deep the heat from deep in the Earth causes the sediments to partially melt, generating belts of magmas that rise to the surface forming magmatic arcs. Although the geosyncline concept is no longer used in geology or tectonics, the work of Stille on correlating tectonic events across Europe and the world is noteworthy. The idea of seafloor spreading was not proposed until a year after Stille died, so he never had the opportunity to place his models and observations into a plate tectonic framework. Stille was instrumental in establishing the global correlation of many geologic events, such as major deformation and magmatic episodes in mountain belts, and this was later important in establishing supercontinent cycles. In this concept, many orogenic events are globally correlated because they occur when most of the planet's landmasses aggregate into one large continent, forming widespread global orogenic events. When the supercontinent breaks up, there is widespread rifting and magmatism around the margins of the fragments breaking off, and plate tectonic drift will separate these fragments so that they are later widely dispersed. Stille's work enabled later geologists to propose many of the events in different parts of the supercontinent cycle.

Stille started out as a chemistry student, but his interest shifted to geology under the influence of German geologist Adolf von Koenen of Göttingen. Stille worked for the Prussian geological survey and then taught in Hannover. In 1912 he became a professor of geology and the director of the Royal Saxon Geological Survey at Leipzig. He was later named professor at the University of Berlin in 1932 and developed a reputation of being an outstanding teacher and philosopher of global tectonics.

Stille was known as a leader in German geology, an outstanding investigator and collator of the history of global tectonic events, and a great teacher. He directed attention to the explanation of the relationships among large crustal features, and his studies of the eugeosynclinal belts led to the interest in their magmatic history. Stille received many honorary doctorates and was elected an honorary member in numerous academics of science, geological societies, and other scientific organizations. He became the honorary president of the German Geological Society, which awarded him the Leopold von Buch Medal and later had the Hans Stille Medal instituted in his honor.

See also BASIN, SEDIMENTARY BASIN; CONTINENTAL DRIFT; DEFORMATION OF ROCKS; EUROPEAN GEOLOGY; PASSIVE MARGIN; PHANEROZOIC; PLATE TECTONICS; SUPERCONTINENT CYCLES.

stratigraphy, stratification, cyclothem

Stratigraphy is the study of rock strata or layers, especially with concern for their succession, age relationships, lithologic composition, geometry, distribution, correlation, fossil content, and other aspects of the strata. The main aim of stratigraphy is to understand and interpret the rock record in terms of paleoenvironments, mode of origin of the rocks, and the causes of similarities and differences between different stratigraphic units. Because sedimentary rocks are laid down one on top of another, examination of successively lower layers in a thick pile of sedimentary rocks, such as those in the Grand Canyon, represents a backward progression in time. The time difference between rocks at the top of the Grand Canyon and those at the base is nearly 2 billion years. Thus, by looking at the different layers, we can reconstruct the past conditions on the planet at this particular place.

These relationships are expressed in several laws of stratigraphy. The first, known as the law of original horizontality, states that water-laid sediments form horizontal strata, parallel to the Earth's surface. So sedimentary rocks that are inclined have been deformed. The second law, the principle of stratigraphic superposition, states that the order in which the strata were deposited is from bottom to top, assuming that the strata have not since been overturned.

The principle of strata superposition permits definition of the relative ages of two different sedimentary units. Simply put, the older rocks are below the younger ones—this is useful for correlating geologic strata from well-exposed to poorly exposed areas, for once the relative age of a unit is known, then it is possible to know which rocks are above and below it. Where rocks are folded or tectonically deformed, some may be upside down, and knowledge of the sequence of units is important for determining whether the rocks in a particular area are right-side up or upside down. One way to tell if rocks are upside down or not is to use the geometry of sedimentary features that formed when the rock was a sediment. For instance, if the original rock showed graded bedding, from coarse-grained at the bottom to fine-grained at the top, and now the rock has fine material at the base and course at the top, it may be upside down. Sand ripples or cross laminations on the bottoms of the beds instead of the tops would also suggest that the strata are upside down.

Although one can determine the relative ages of strata by their position with respect to one another, the absolute ages cannot be determined in this manner, nor can the intervals of time between the different units. One reason for this is that deposition is not continuous; the stratigraphic record might contain breaks or discontinuities, represented by unconformities.

STRATIGRAPHIC CLASSIFICATION

Because rocks laid down in succession each record environmental conditions on the Earth when they were deposited, experienced geologists can read the record in the stratigraphic pile like a book recording the history of time. Places like the Grand Canyon are especially spectacular because they record billions of years of history.

Classical stratigraphy is based on the correlation of distinct rock stratigraphic units, or unconformity surfaces, that are internally homogeneous and occur over large geographic areas. The basic unit of rock stratigraphy is the formation, defined as a group of strata which constitutes a distinctive recognizable unit for geologic mapping purposes. Thus, a formation must be thick enough to show up on a map, must be laterally extensive, and must be distinguishable from surrounding strata. Formations are named according to a code (the Code of North American Stratigraphic Nomenclature), using a prominent local geographic feature. Formations are divided into members and beds, according to local differences or regionally distinctive horizons. Formations are sometimes combined together with other formations into groups.

A more recent advance in stratigraphy is time stratigraphy, that is, the delineation of stratigraphic units by time. Units divided in this manner have lower and upper boundaries that are the same age everywhere, but may look very different and comprise different rock types. Fossils known to occur only during a certain period or correlating unconformities (erosional surfaces) that have approximately the same age in different places help identify time-stratigraphic units. The primary unit of time stratigraphy is the system, which is an interval so great that it can be recognized over the entire planet. Most systems represent time periods of at least tens of millions of years. Larger groups of systems are called erathems or eras for short. Time units smaller than the system are series and stage, terms typically used for describing correlations on a single continent or within a geographic province.

TIMELINES AND DIACHRONOUS BOUNDARIES

In many sedimentary systems, such as the continental shelf, slope, and rise, different types of sediments are deposited in different places at the same time. We can draw time lines through these sequences to represent all the sediments deposited at a given time or to represent the old sediment/water interference at a given time. In these types of systems, the transition from one rock type to another, such as from the sandy delta front to the marsh facies, will be diachronous in time (it will have different ages in different places).

CORRELATION OF ROCKS

If a geologist has studied a stratigraphic unit or system in one location and figured out conditions on the Earth at that point when the rock was deposited, this information can be related to the rest of the planet or simply to nearby areas. In order to accomplish this task, the geologist first needs to determine the relative ages of strata in a column, then estimate the absolute ages relative to a fixed time scale. One can determine correlations between stratigraphic units locally using various physical criteria, such as continuous exposure where a formation is recognizable over large areas. Typically, a group of characteristics for each formation distinguishes it from other formations. These include gross lithology or rock type, mineral content, grain size, grain shape, color, or distinctive sedimentary structures such as cross-laminations. Occasionally, key beds with characteristics so distinctive that they are easily recognized are used for correlating rock sections.

Most sedimentary rocks lie buried beneath the surface layer on the Earth, and geologists and oil companies interested in correlating different rock units have to rely on data taken from tiny drill holes. The oil companies in particular have developed many clever ways of correlating rocks with distinctive (oil rich) properties. One common method is to use well logs, where the electrical and physical properties of the rocks on the side of the drill hole are measured, and distinctive patterns between different wells are correlated. This helps the oil companies in relocating specific horizons that may be petroleum-rich.

Index fossils are those that have a wide geographic distribution and occur commonly but have a restricted time interval in which they formed. Because the best index fossils should be found in many environments, most are floating organisms that can travel quickly around the planet. If the index fossil is found at a certain stratigraphic level, often its age is well known, and it can be correlated with other rocks of the same age.

See also BASIN, SEDIMENTARY BASIN; MILANKOVITCH CYCLES; SEDIMENTARY ROCK, SEDIMENTATION; SEQUENCE STRATIGRAPHY.

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structural geology Structural geology is the study of the deformation of the Earth’s crust or lithosphere. The surface of the Earth is actively deforming, as demonstrated by evidence such as earthquakes and active volcanism and from rocks at the surface of the Earth that have been uplifted from great depths. The rates of processes (or time scales) of structural geology are very slow compared to ordinary events. For instance, the San Andreas fault moves only about an inch (a couple of centimeters) a year and is considered relatively fast for a geological process. Even this process is discontinuous near the surface, with major earthquakes happening every 50–150 years. At great depths the movement between the plates may be accommodated by more continuous flowing types of deformation, instead of the stick-slip type of behavior that occurs near the surface. Mountain ranges such as the Alps, Himalayas, or those in the American West are uplifted at rates of a fraction of an inch (a few millimeters) a year, with heights of a mile or two (several kilometers) being reached in a few million years. These types of processes have been happening for billions of years, and structural geology attempts to understand the current activity and this past history of the Earth's crust.

Structural geology and tectonics are both concerned with reconstructing the motions of the outer layers of the Earth. The terms have similar roots—structure comes from the Latin *struere,* meaning to build, whereas tectonics comes from the Greek *tektos,* meaning builder.

Rigid body rotations are one type of motion of the surface of the Earth in which a unit of rock is transported from one place to another without a change in size and shape. These types of motions fall under the scope of tectonics. In contrast, deformations are motions involving a change in the shape and size of a unit of rock, something that falls under the realm of structural geology.

When motions occur at faults or when mountains are uplifted, rocks break at shallow levels of the crust and flow like soft plastic at deeper levels of the crust. These processes occur at all scales, ranging from the scale of plates, continents, and regional maps to what is observable only using electron microscopes.

Structural geology and tectonics have changed dramatically since the 1960s. Before 1960, structural geology was a purely descriptive science, and since then has become an increasingly quantitative discipline, especially applying principles of continuum mechanics, with increasing use of laboratory experiments and the microscope to understand the mechanisms of deformation.

Tectonics has also undergone a recent revolution (since the understanding of plate tectonics in the 1960s) that provided a framework for understanding the large-scale deformation of the crust and upper mantle. Both structural geology and tectonics have made extensive use of new tools since the 1960s, including geophysical data (e.g., seismic lines), paleomagnetism, electron microscopes, petrology, and geochemistry.

Most studies in structural geology rely on field observations of deformed rocks at the Earth's surface and proceed either downscale to microscopic observations or upscale to regional observations. None of these observations alone provides a complete view of structural and tectonic processes, so structural geologists must integrate observations at all scales and use the results of laboratory experiments and mathematical calculations to interpret observations better.

To work out the structural or tectonic history of an area, the geologist will usually proceed in a logical order. First, the geologist systematically observes and records structures (folds, fractures, contacts) in the rock, usually in the field. This consists of determining the geometry of the structures, including their geographical location, orientation, and characteristics. Additionally, the structural geologist is concerned with determining the number of times a rock has been deformed and which structures belong to which deformation episode.

The term *attitude* means the orientation of a plane or line in space. Attitude is measured using two angles—one measured from geographic north and the other from a horizontal plane. The attitude of a plane is represented by a strike and a dip, whereas the attitude of a line is represented by a trend and plunge. Strike is the horizontal angle, measured relative to geographic north of the horizontal line in a given planar structure. The horizontal line is referred to as the strike line, and is the intersection of a horizontal plane with the planar structure. One can easily measure strike in the field with a compass, by holding the compass against the plane and keeping the compass horizontal. Dip is the slope of the plane defined by the dip angle and the dip direction, which must be specified. It is the acute angle between a horizontal plane and the planar structure, measured in a vertical plane perpendicular to the strike line.

To understand the processes that occurred in the Earth, structural geologists must also examine the kinematics of formation of the structures; that is, the motions that occurred in producing them. This will lead to a better understanding of the mechanics of formation, including the forces that were applied, how they were applied, and how the rocks reacted to the forces to form the structures.

To improve understanding of these aspects of structural geology, geologists make conceptual models of how the structures form and test predictions of these models against observations. Kinematic models describe a specific history of motion that could have carried the system from one configuration to another (typically from an undeformed to a deformed state). Such models are not concerned with why or how motion occurred or the physical properties of the system (plate tectonics is a kinematic model).

Mechanical models are based on continuum mechanics (conservation of mass, momentum, angular momentum, and energy) and an understanding of how rocks respond to applied forces (based on laboratory experiments). With mechanical models geologists can calculate the theoretical deformation of a body subjected to a given set of physical conditions of forces, temperatures, and pressures (an example of this is the driving forces of tectonics based on convection in the mantle). Mechanical models represent a deeper level of analysis than kinematic models, constrained by geometry, physical conditions of deformation, and the mechanical properties of rocks.

One must remember, however, that models are only models, and they only approximate the true Earth. Models are built through observations and allow one to make predictions that can be tested to draw conclusions concerning the model's relevance to the real Earth. New observations can support or refute a model. If new observations contradict predictions, models must be modified or abandoned.

STRUCTURAL GEOLOGY AND THE INTERIOR OF THE EARTH

Structures at the surface of the Earth reflect processes occurring at deeper levels. We know that the Earth is divided into three concentric shells—the core, mantle, and crust. The core is a very dense iron-nickel alloy, comprising the solid inner core and the liquid outer core. The mantle is composed of lower-density, solid magnesium-iron silicates, and is actively convecting, transporting heat from the interior of the Earth to the surface. This heat transfer is the main driving mechanism of plate tectonics. The crust is the thin, low-density rock material making up the outer shell of the Earth.

Temperature increases with depth in the Earth at a gradient of about 54°F per half a mile (30°C/km) in the crust and upper mantle, and with a much smaller gradient deeper within Earth. The heat of the Earth comes from several different sources, including residual heat trapped from initial accretion, radioactive decay, latent heat of crystallization of the outer core, and dissipation of tidal energy of the Sun-Earth-Moon system.

Heat flows out of the interior of the Earth toward the surface through convection cells in the outer core and mantle. The top of the mantle and the crust form a relatively cold and rigid boundary layer called the lithosphere, which is about 61 miles (100 km) thick. Heat escapes through the lithosphere largely by conduction, transport of heat in igneous melts, and in convection cells of water through mid-ocean ridges.

Structural geologists predominantly study only the outer 12–18 miles (20–30 km) of the lithosphere. This puts into perspective how much structural geology infers a great deal about the interior of the Earth by examining only its skin.

CHARACTERISTICS OF THE CRUST

Earth's crust is divisible broadly into continental crust of granitic composition and oceanic crust of basaltic composition. Continents comprise 29.22 percent of the surface, whereas 34.7 percent of Earth's surface is underlain by continental crust (continental crust under submerged continental shelves accounts for the difference). The continents are in turn divided into orogens, made of linear belts of concentrated deformation, and cratons, the stable, typically older interiors of the continents.

Hypsometric diagrams reflect the strongly bimodal distribution of surface elevation. Continental freeboard, the difference in elevation between the continents and ocean floor, results from differences in thickness and density between continental and oceanic crust, tectonic activity, erosion, sea level, and strength of continental rocks.

CONTROLS OF DEFORMATION

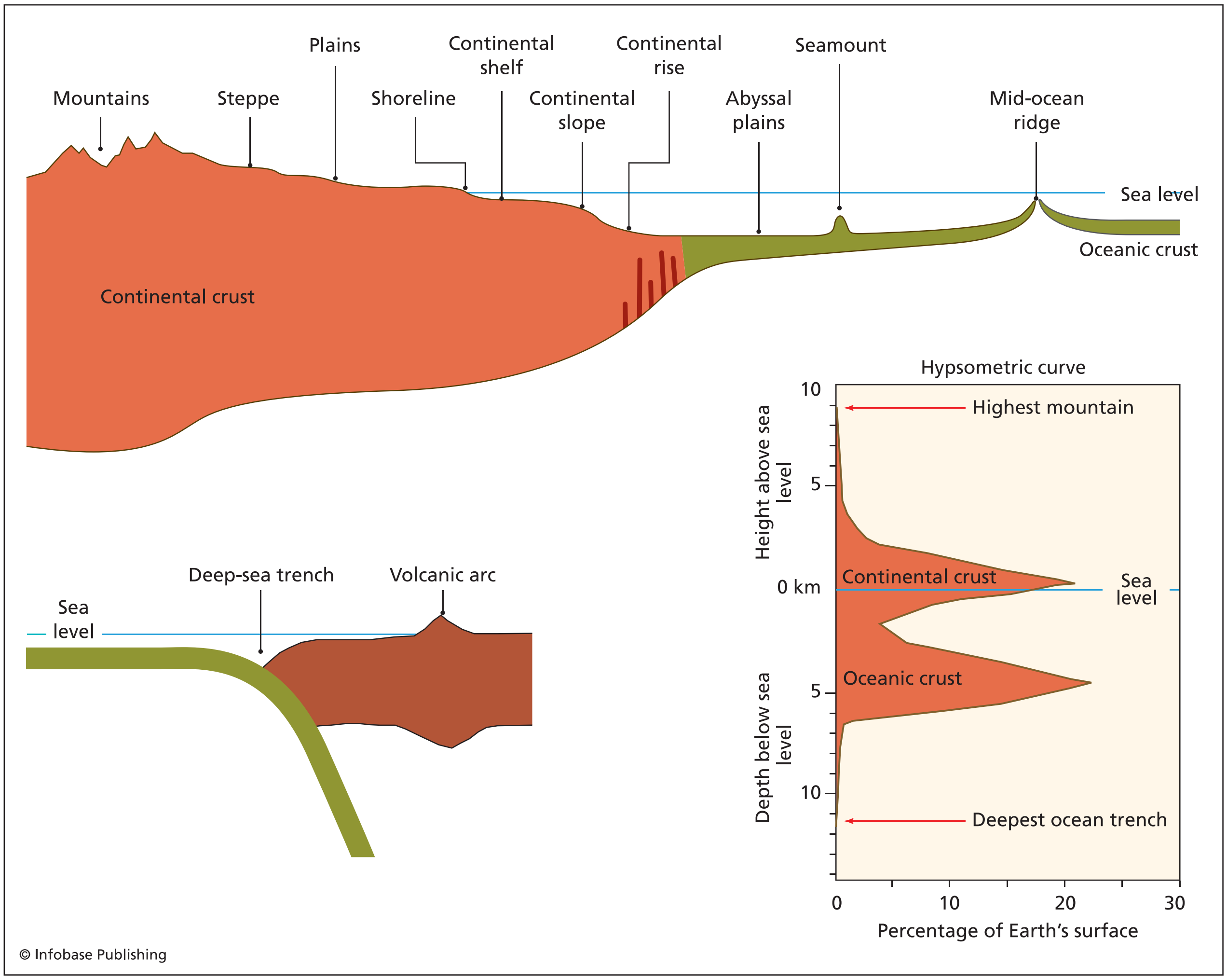
Deformation of the lithosphere is controlled by the strength of rocks, which in turn depends mostly on temperature and pressure. Strength increases with pressure and decreases exponentially with increasing temperature. Because temperature and pressure both increase downward, a cross section through the crust or lithosphere will have different zones where the effects of either pressure or temperature dominate.

In the upper layers of the crust, effects of pressure dominate, and rocks that are subject to high stress will fail with brittle processes such as fracturing. Rocks grow stronger with depth with increasing pressure until about nine miles (15 km) depth. At this point, the effects of temperature become increasingly more important; the rocks get weaker as they get hotter, and the rocks deform by different mechanisms including flowing ductile deformation.

Other important properties that determine how the lithosphere deforms are composition (e.g., quartz versus olivine in crust, mantle, continents, and oceans) and strain rate, a measure of how fast a rock is deformed. The greatest variations in strain rate occur along plate boundaries, and most structures develop as a consequence of plate interactions along plate boundaries.

STRUCTURAL GEOLOGY AND PLATE TECTONICS

The surface of the Earth is divided into 12 major and several minor plates that are in motion with respect to each other. Plate tectonics describes these relative motions, which are, to a first approximation, rigid body rotations. However, deformation of the plates does occur (primarily in belts tens to hundreds of kilometers in width along the plate boundaries), and in a few places, extends into the plate interiors. Structural geology deals with these deformations,



Hypsometric curve showing the distribution of land with different elevations on the planet. Note the bimodal distribution, reflecting two fundamentally different types of crust (oceanic and continental) that have different isostatic compensation levels. Cross sections show a typical continental margin–ocean transition and ocean trench–island arc boundary.

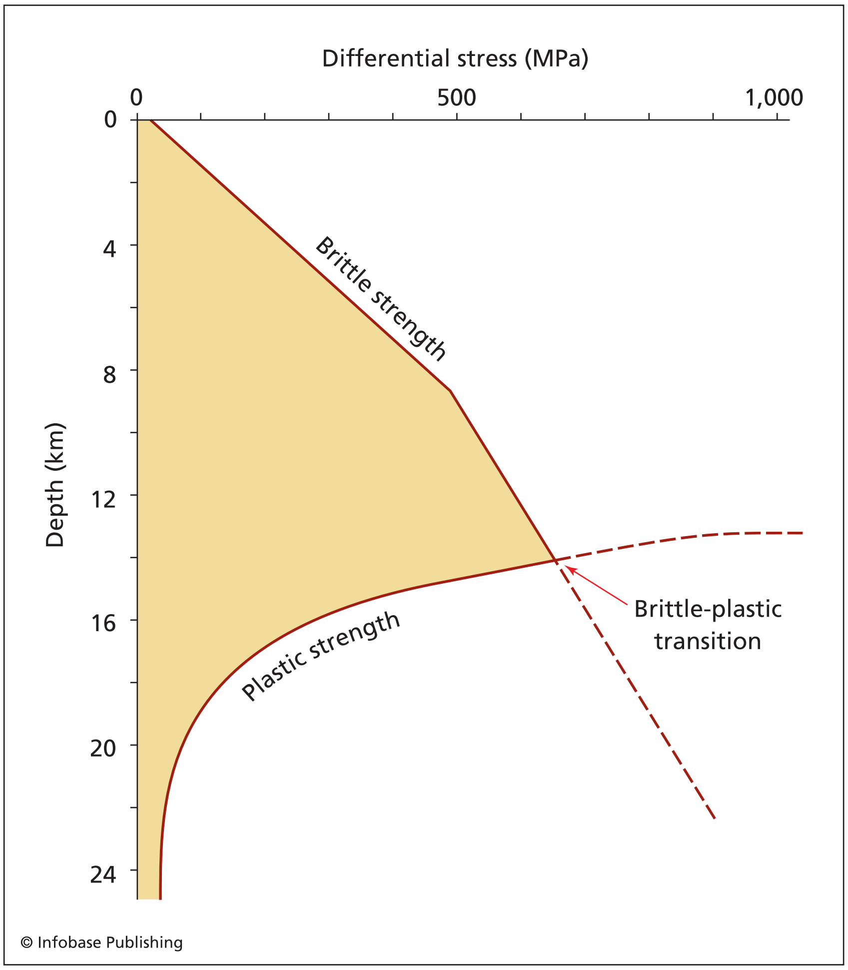
which in turn give clues to the types of plate boundary motions that have occurred and to the tectonic causes of the deformation.

Plate boundaries may be divergent, convergent, or conservative/transform. The most direct evidence for plate tectonics comes from oceanic crust, which has magnetic anomalies or stripes recording plate motions. However, the seafloor magnetic record goes only as far back as 180 million years, the age of the oldest in-place oceanic crust. Any evidence for plate tectonics in the preceding 96 percent of Earth history must come from studying the continents (structural geology).

Highly deformed continental rocks are concentrated in long linear belts called orogens, comparable to those associated with modern plate boundaries. This observation suggests that these belts represent former plate boundaries. The structural geologist examines these orogens, determines the geometry, kinematics, and mechanics of these zones, and makes models for the types of plate boundaries that created them. The types of structures that develop during deformation depend on the orientation and intensity of applied forces, the physical conditions (temperature and pressure) of deformation, and the mechanical properties of rocks.

The most important forces acting on the lithosphere that drive plate tectonics and cause the deformation of rocks are the gravitational "ridge push" down the flanks of oceanic ridges, gravitational "trench pull" of subducting lithosphere caused by its greater density than surrounding asthenosphere, and the resistance of trenches and mountain belts.

At low temperature and pressure and high intensity of applied forces, rocks undergo brittle deformation, forming fractures and faults. At high temperature



The strength of the lithosphere changes dramatically with pressure and temperature, based on the mechanical properties of the minerals in the rocks at different depths. There are several weak and strong zones at different depths that vary in depth in different parts of the world based on the different rock types in different places.

and pressure and low intensity of applied forces, rocks undergo ductile deformation by flow, coherent changes in shape, folding, stretching, thinning, and many other mechanisms.

Different styles of deformation characterize different types of plate boundaries. For instance, at mid-ocean ridges new material is added to the crust, and relative divergent motion of the plates creates systems of extensional normal faults and ductile thinning at depth. At convergent plate boundaries, one plate is typically subducted beneath another, and material is scraped off the down-going plate in a system of thrust faults and folds. Along transform plate boundaries, systems of strike-slip faults merge downward with zones of ductile deformation with horizontal relative displacements. All types of plate boundaries have small-scale structures in common, so it is necessary to carefully examine regional patterns before making inferences about the nature of ancient plate boundaries.

STRESS

Stress is the total force exerted by all the atoms on one side of an arbitrary plane upon the atoms immediately on the other side of the plane. Stress is what causes rocks to deform, so understanding the concepts of stress is essential to structural geology. Body forces are those that act from a distance (e.g., gravity) and are proportional to the amount of material present. Surface forces are those that act across surfaces of contact between parts of bodies, including all possible internal surfaces. There are two kinds of surface forces, including normal (compressive and tensile) that act perpendicular to the surface and shear (clockwise and anticlockwise) that act parallel to the surface. The state of stress equals the force divided by the area across which it acts.

For any applied force, it is possible to find a choice of coordinate axes such that all shear stresses are equal to zero, and only three perpendicular principal stresses have nonzero values. The principal stresses, commonly abbreviated σ1, σ2, and σ3, are parallel to the semimajor axes of an ellipsoid called the stress ellipsoid, parallel to the coordinate axes chosen such that they are the only nonzero stresses.

The deviatoric stress, or the difference between the principal stresses, is most important for forming structures in rocks, because it drives the deformation. However, the mean stress, given by

$$\frac{(\sigma1 + \sigma2 + \sigma3)}{3},$$

is important for determining which deformation mechanisms operate and the strength of materials.

Stress has dimensions of force per unit area. In the SI system, stress is reported in Pascals (Pa), which is equal to one Newton per meter squared (N/m^2).

$$1\ \mathrm{Pa} = \frac{\mathrm{N}}{\mathrm{M}^2}\ ,$$

The sign convention that geologists use considers compressive stresses to have a positive sign.

STRAIN

Strain is a measure of the relationship between size and shape of a body before and after deformation. Strain is one component of a *deformation,* a term that includes a description of the collective displacement of all points in a body. Deformation consists of three components: rigid body rotation, a rigid body translation, and a distortion known as strain. Strain is typically the only visible component of deformation, manifest as distorted objects, layers, or geometric constructs.

There are many measures of strain: changes in lengths of lines, changes in angles between lines, changes in shapes of objects, and changes in volume or area. The change in the length of lines can be quantified using several different strain measures.

$$\text{Extension } (\varepsilon) = \frac{(L' - L)}{L}$$

where L is the original length of line, and L′ is the final length of line;

$$\text{Stretch } (S) = \frac{L'}{L} = (1 - \varepsilon)\ .$$

The quadratic elongation

$$\lambda_{.} = \left(\frac{L'}{L}\right)^2 = (1 - \varepsilon)^2\,,$$

whereas the natural or logarithmic strain is expressed as: (ε)

$$\varepsilon = \log e\left(\frac{L'}{L}\right) = \log e(1 - \varepsilon)\,.$$

The change of angles is typically measured using the angular shear (ψ angular shear), which is the change in the angle between two lines that were initially perpendicular. More commonly, structural geologists measure angular strain using the tangent of the angular shear, known as the shear strain:

$$\gamma = \tan \psi$$

Volumetric strain is a measure of the change in volume of an object, layer, or region. Dilation (δ) measures the change in volume:

$$(\Delta) = \frac{(V' - V)}{V}\ ,$$

whereas the volume ratio

$$\frac{V'}{V}$$

measures the ratio of the volume after and before deformation.

Strains may be homogeneous or heterogeneous. Heterogeneous strains are extremely difficult to analyze, so the structural geologist interested in determining strain typically focuses on homogeneous domains with the heterogeneous strain field. In contrast, the geologist interested in tectonic problems involving large-scale translation and rotation often finds it necessary to focus on zones of discontinuity in the homogeneous strain field, as these are often sites of faults and high strain zones along which mountain belts and orogens have been transported. For homogeneous strains, the following five general principles hold true: straight lines remain straight and flat planes remain flat; parallel lines remain parallel and are extended or contracted by the same amount; perpendicular lines do not remain perpendicular unless they are oriented parallel to the principal strain axes; circular markers are deformed into ellipses; finally, there is one special initial ellipsoid that becomes a sphere when deformed. When these conditions are met, the strain field is homogeneous, and strain analysis of deformed objects indicates the strain of the whole body.

Structural geologists often find it important to measure the strain in deformed rocks in order to reconstruct the history of mountain belts, to determine the amount of displacement across a fault or shear zone, or to accurately delineate the distribution of an ore body—this process is called strain analysis. To measure strain in deformed rocks, the geologist searches for features that had initial shapes that are known and can be quantified, such as spheres (circles), linear objects, or objects like fossils that had initial angles between lines that are known. In most cases, geologists cannot directly see the three-dimensional shape of deformed objects in rocks. Strain analysis proceeds by measuring the two-dimensional shapes of the objects on several different planes at angles to each other. The deformed shapes are graphically or algebraically fitted together to get the three-dimensional shape of the deformed object and ultimately the three-dimensional shape and orienta-

Ooids in limestone showing a small amount of deformation. Sample is 1.3 inches (3.3 cm) tall. *(Dirk Wiersma/Photo Researchers, Inc.)*

tion of the strain ellipsoid. The strain ellipsoid has major, intermediate, and minor axes of X, Y, and Z, parallel to the principal axes of strain.

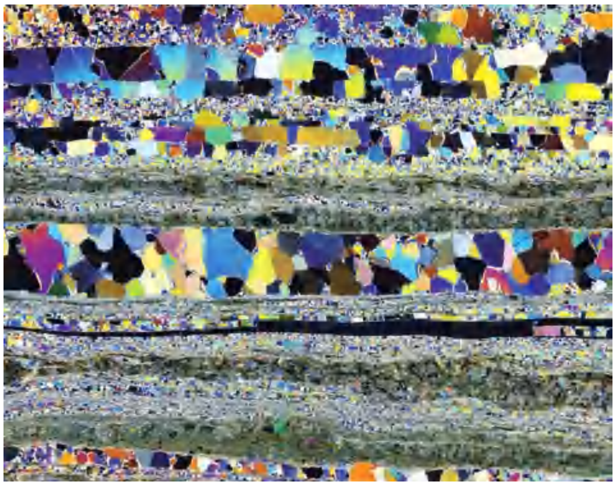
Structural geologists interested in determining the strain of a body search for appropriate objects to measure the strain. Initially spherical objects prove to be among the most suitable for estimating strain. Any homogeneous deformation transforms an initial sphere into an ellipsoid whose principal axes are parallel to the principal strains, and whose lengths are proportional to the principal stretches S1, S2, and S3. Using elliptical markers that were originally circular, one can immediately tell the orientation of the principal strains on that surface and their relative magnitudes. However, the true values of the strains are not immediately apparent, because the original volumes are not typically known. Strain markers in rocks that serve as particularly good recorders of strain and approximate initially circular or spherical shapes include conglomerate clasts, ooids, reduction spots in slates, certain fossils, and accretionary lapilli.

Angular strain is often measured using the change in angles of bilaterally symmetric fossils, or igneous dikes cutting across shear zones. Many fossils, such as trilobites and clams, are bilaterally symmetric, so if line of symmetry can be found, similar points on opposite sides of the plane of symmetry can be joined, and the change in the angles from the initially right angles in the undeformed fossils can be constructed. When the fossils are deformed, the right angles are also deformed, and the same relationships derived above for change in angles can be used to determine the angular strain of the sample.

Strain represents the change from the initial to the final configuration of a body, but it tells us very little about the path the body took to get to the final shape, known as the deformation path. The strain represents the combination of all events that occurred, but they are by no means unique. Fortunately, rocks have a memory, and there are many small-scale structures and textures in the rocks that tell us much about where the rock has been, or what its deformation path was. One of the most important attributes of the strain path to determine is whether the principal strain axes were parallel between each successive strain increment or not. A coaxial deformation is one in which the principal axes of strain are parallel with each successive increment. A noncoaxial deformation is one in which the principal axes of strain rotate with respect to the material during deformation.

Two special geometric cases of strain history are pure shear and simple shear. A pure shear is a coaxial strain (with no change in volume). Simple shear is analogous to sliding a deck of cards over itself and is a two-dimensional noncoaxial rotational strain, with constant volume and no flattening perpendicular to the plane of slip.

In simple shear, the principal axes rotate in a regular manner. The principal strain axes start out at 45° to the shear plane, and strain S1 rotates into parallelism with it at very high (infinite) strains. The



Microscopic view in polarized light of mylonite. Mica rich layers are dark, while quartz layers are colorful, with polygonal shapes of individual grains. *(Dirk Wiersma/Photo Researchers, Inc.)*

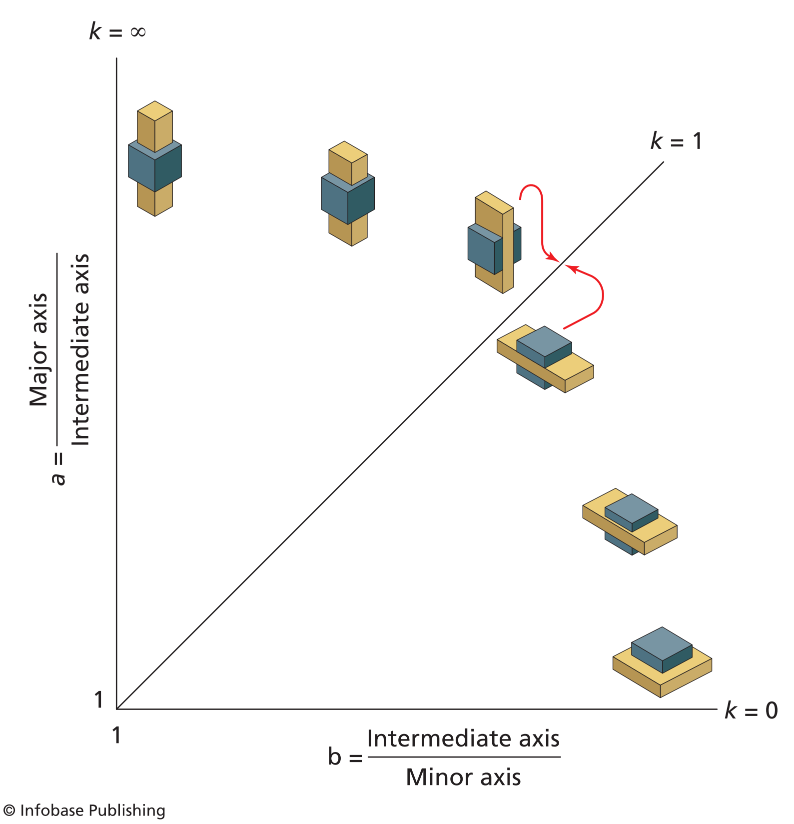
principal axes remain perpendicular, but some other lines will be lengthening with each increment, and others will be shortening. There are some orientations that experience shortening first, and then lengthening. This leads to some complicated structures in rocks deformed by simple shear; for instance, folds produced by the shortening, and then extensional structures, such as faults or pull-apart structures known as boudens, superimposed on the early contractional structures.

Natural strains in rocks deform initially spherical objects into ellipsoids with elongate (prolate) or flattened (oblate) ellipsoids. All natural strains may be represented graphically on a graph known as a Flynn Diagram, which plots a = (X/Y) versus b = (Y/Z). The number

$$k = \frac{(a-1)}{(b-1)} \ .$$

For k= 0, strain ellipsoids are uniaxial oblate ellipsoids or pancakes. For 0 > k > 1, deformation is a flattening deformation, forming an oblate ellipsoid. For k = 1 the deformation is plane strain if the volume has remained constant. All simple shear deformations lie on this line. For 1 > k > infinity, the strain ellipsoids are uniaxial prolate ellipsoids, or cigar shapes.

See also CONVERGENT PLATE MARGIN PROCESSES; DEFORMATION OF ROCKS; DIVERGENT PLATE MARGIN PROCESSES; FRACTURE; MÉLANGE; METAMORPHISM AND METAMORPHIC ROCKS; PLATE TECTONICS; TRANSFORM PLATE MARGIN PROCESSES.



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Flynn diagram showing fields of prolate, oblate, and plane strain

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subduction, subduction zone Subduction zones are long, narrow belts where an oceanic lithospheric plate descends beneath another lithospheric plate and enters the mantle in the processes of subduction. Two basic types of subduction zones exist, the first of which being where oceanic lithosphere of one plate descends beneath another oceanic plate, such as in the Philippines and Marianas of the southwest Pacific. The second type of subduction zone forms where an oceanic plate descends beneath a continental upper plate, such as in the Andes of South America. Deep-sea trenches typically mark the place on the surface where the subducting plate bends to enter the mantle, and oceanic or continental margin arc systems form above subduction zones a couple of hundred miles (a few hundred kilometers) from the trench. As the oceanic plate enters the trench it must bend, forming a flexural bulge up to a few thousand feet (a couple of hundred meters) high, typically about 100 miles (161 km) before the oceanic plate enters the trench. A series of down-to-the-trench normal faults marks the outer trench slope on the downgoing plate, in most cases. Trenches may be partly or nearly entirely filled with sediments, many of which become offscraped and attached to the accretionary prism on the overriding plate. The inner trench slope on the overriding plate typically is marked by these folded and complexly faulted and offscraped sediments, and distinctive disrupted complexes known as mélanges may form in this environment.

In ocean-ocean subduction systems the arc develops about 100–150 miles (150–200 km) from the trench. Immature or young oceanic island arcs are dominated by basaltic volcanism and may be mostly underwater, whereas mature systems have more intermediate volcanics and have more of the volcanic edifice protruding above sea level. A forearc basin, filled by sediments derived from the arc and uplifted parts of the accretionary prism, typically occupies the area between the arc and the accretionary prism. Many island arcs have back-arc basins developed on the opposite side of the arc, separating the arc from an older rifted arc or a continent.

Ocean-continent subduction systems are broadly similar to ocean-ocean systems, but the magmas must rise through continental crust so are chemically contaminated by this crust, becoming more silicic and enriched in certain sialic elements. Basalts, andesites, dacites, and even rhyolites are common in continental margin arc systems. Ocean-continent subduction systems tend to also have concentrated deformation, including deep thrust faults, fold/thrust belts on the back-arc side of the arc, and significant crustal thickening. Other continental margin arcs experience extension and may see rifting events that open back-arc basins that extend into marginal seas, or close. Extensive magmatic underplating also aids crustal thickening in continental margin subduction systems.

Oceanic plates may be thought of as conductively cooling upper boundary layers of the Earth's convection cells, and in this context subduction zones are the descending limbs of the mantle convection cells. Once subduction is initiated, the sinking of the dense downgoing slabs provides most of the driving forces needed to move the lithospheric plates and force seafloor spreading at divergent boundaries where the mantle cells are upwelling.

The amount of material cycled from the lithosphere back into the mantle of the Earth in subduction zones is enormous, making subduction zones the planet's largest chemical recycling systems. Many of the sedimentary layers and some of the upper oceanic crust are scraped off the downgoing slabs and added to accretionary prisms on the front of the overlying arc systems. Hydrated minerals and sediments release much of their trapped seawater in the upper couple hundred miles (few hundred kilometers) of the descent into the deep Earth, adding water to the overlying mantle wedge and triggering melting that supplies the overlying arcs with magma. The material that is not released or offscraped and underplated in the upper couple hundred miles (few hundred kilometers) of subduction forms a dense slab that may go through several phase transitions and either flatten out at the 416-mile (670-km) mantle discontinuity or descend all the way to the core-mantle boundary. The slab material then rests and is heated at the core-mantle boundary for about a billion years, after which it may form a mantle plume that rises through the mantle to the surface. In this way, an overall material balance is maintained in subduction zone-mantle convection-plume systems.

Most continental crust has been created in subduction zone-arc systems of various ages stretching back to the Early Archean.

See also ACCRETIONARY WEDGE; ANDES MOUNTAINS; CONVERGENT PLATE MARGIN PROCESSES; MANTLE PLUMES; MÉLANGE; OCEAN BASIN; OPHIOLITES; PLATE TECTONICS.

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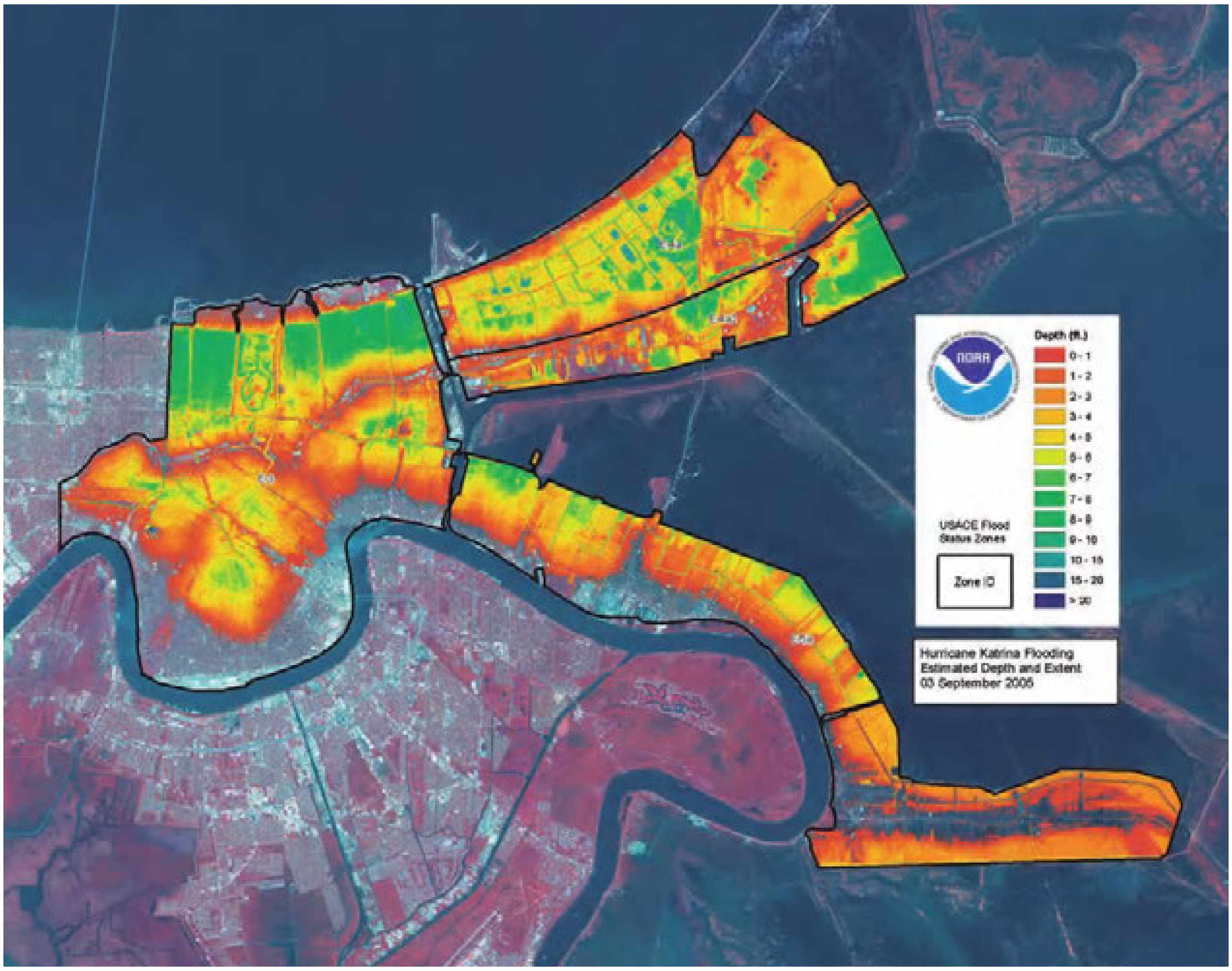
subsidence Natural geologic subsidence is the sinking of land relative to sea level or some other uniform surface. Subsidence may be a gradual, barely perceptible process, or it may occur as a catastrophic collapse of the surface. Subsidence occurs naturally along some coastlines and in areas where groundwater has dissolved cave systems in rocks such as limestone. It may occur on a regional scale, affecting an entire coastline or it may be local in scale, such as when a sinkhole suddenly opens and collapses in the middle of a neighborhood. Other subsidence events reflect the interaction of humans with the environment and include ground surface subsidence as a result of mining excavations, groundwater and petroleum extraction, and several other processes.

Compaction is a related phenomenon, where the pore spaces of a material are gradually reduced, condensing the material and causing the surface to subside. Subsidence and compaction do not typically result in death or even injury, but they do cost Americans alone tens of millions of dollars per year. The main hazard of subsidence and compaction is damage to property.

Coastal subsidence, which is equated with a local sea level rise, can also result in more sinister long-term effects. Many coastal cities are experiencing slow subsidence so that surfaces once above sea level sink to many feet below sea level over hundreds of years. This phenomenon results in putting cities including Venice, New Orleans, and many others below sea level. In the case of New Orleans, the subsidence has caused the surrounding wetlands to have sunk below sea level, placing the city—now partly below sea level—much closer to the coast than when it was built. Subsidence has therefore contributed greatly to the increased damage to the city from recent hurricanes, including Katrina and Rita in 2005, and continues to place the city at ever-increasing risk.

Subsidence and compaction of the land (and relative rise of sea level) directly affect millions of people. Residents of New Orleans live below sea level and are constantly struggling with the consequences of living on a slowly subsiding delta. Coastal residents in the Netherlands have constructed massive dike systems to try to keep the North Sea out of their slowly subsiding land. The city of Venice, Italy, has dealt with subsidence in a uniquely charming way, drawing tourists from around the world. Millions of people live below the high-tide level in Tokyo. The coastline of Texas along the Gulf of Mexico is slowly subsiding, placing residents of Baytown and other Houston suburbs close to sea level and in danger of hurricane-induced storm surges and other more frequent flooding events. In Florida, sinkholes have episodically opened up swallowing homes and businesses, particularly during times of drought.



Flood depth estimation map of New Orleans, September 3, 2005 *(NOAA)*

The driving force of subsidence is gravity, with the style and amount of subsidence controlled by the physical properties of the soil, regolith, and bedrock underlying the area that is subsiding. Subsidence does not require a transporting medium, but it is aided by other processes such as groundwater dissolution that can remove mineral material and carry it away in solution, creating underground caverns that are prone to collapse.

Natural subsidence has many causes, all of which may operate in the coastal environment. Dissolution of limestone by underground streams and water systems is one of the most common, creating large open spaces that collapse under the influence of gravity. Groundwater dissolution results in the formation of sinkholes, large, generally circular depressions caused by collapse of the surface into underground open spaces.

Earthquakes may raise or lower the land suddenly, as in the case of the 1964 Alaskan earthquake where tens of thousands of square miles suddenly sank or rose 35 feet (11.5 m), causing massive disruption to coastal communities and ecosystems. Earthquake-induced ground shaking can also cause liquefaction and compaction of unconsolidated surface sediments, also leading to subsidence. Regional lowering of the land surface by liquefaction and compaction was widespread in the magnitude 6.9 Kobe, Japan, earthquake of 1995.

Volcanic activity can cause subsidence, as when underground magma chambers empty out during an eruption. In this case, subsidence is often the lesser of many hazards that local residents need to fear. Subsidence may also occur on lava flows, when lava empties out of tubes or underground chambers. The eruption of Krakatua in Indonesia in 1883 was associated with rapid collapse of the coastal caldera, and the sea rushed into the exposed magma chamber, generating a huge tsunami that killed 36,000 people in nearby coastal villages.

Some natural subsidence on the regional scale is associated with continental scale tectonic processes. The weight of sediments deposited along continental shelves can cause the entire continental margin to sink, causing coastal subsidence and a landward migration of the shoreline. Tectonic processes associated with extension, continental rifting, strike-slip faulting, and even collision can cause local or regional subsidence, sometimes at rates of several inches (7–10 cm) per year.

TYPES OF SURFACE SUBSIDENCE AND COLLAPSE

Some subsidence occurs because of processes that happen at depths of thousands of feet beneath the surface, and is referred to as deep subsidence. Other subsidence is caused by shallow near-surface processes and is known as shallow subsidence. Tectonic subsidence is a result of the movement of the plates on a lithospheric scale, whereas human-induced subsidence refers to cases where the activities of people, such as extraction of fluids from depth, have resulted in lowering of the land surface.

Compaction-related subsidence may be defined as the slow sinking of the ground surface because of reduced pore space, lowered pore pressure, and other processes that cause the regolith to become more condensed and occupy a smaller volume. Most subsidence and compaction mechanisms are slow and result in gradual sinking of the land surface, whereas sometimes the process may occur catastrophically, and is known as collapse.

HUMAN-INDUCED SUBSIDENCE

Several types of human activity can result in the formation of sinkholes or cause other surface subsidence phenomena. Withdrawals of fluids from underground aquifers, depletion of the source of replenishment to these aquifers, and collapse of underground mines can all cause surface subsidence. In addition, vibrations from drilling, construction, or blasting can trigger collapse events, and the extra load of buildings over unknown deep collapse structures can cause them to propagate to the surface, forming a sinkhole. These processes reflect geologic hazards caused by humans' interaction with the natural geologic environment.

Groundwater Extraction

The extraction of groundwater, oil, gas, or other fluids from underground reservoirs can cause significant subsidence of the land's surface. In some cases the removal of underground water is natural. During times of severe drought, soil moisture may decrease dramatically and drought-resistant plants with deep root systems can draw water from great depths, reaching a hundred feet or more (many tens of meters) in some cases. In most cases, however, subsidence caused by deep fluid extraction is caused by human activity.

This deep subsidence mechanism operates because the fluids that are extracted served to help support the weight of the overlying regolith. The weight of the overlying material places the fluids under significant pressure, known as hydrostatic pressure, that keeps the pressure between individual grains in the regolith at a minimum. This in turns helps prevent the grains from becoming closely packed or compacted. If the fluids are removed, the pressure between individual grains increases and the grains become more closely packed and compacted, occupying less space than before the fluid was extracted. This can cause the surface to subside. A small amount of this subsidence may be temporary, or recoverable, but generally once surface subsidence related to fluid extraction occurs, it is non-recoverable. When this process occurs on a regional scale, the effect can be subsidence of a relatively large area. Subsidence associated with underground fluid extraction is usually gradual but still costs millions of dollars in damage every year in the United States.

The amount of surface subsidence is related to the amount of fluid withdrawn from the ground and also to the compressibility of the layer that the fluid has been removed from. If water is removed from cracks in a solid igneous, metamorphic, or sedimentary rock, then the strength of the rock around the cracks will be great enough to support the overlying material and no surface subsidence is likely to occur. In contrast, if fluids are removed from a compressible layer such as sand, shale, or clay, then significant surface subsidence may result from fluid extraction. Clay and shale have a greater porosity and compressibility than sand, so extraction of water from clay-rich sediments results in greater subsidence than the same amount of fluid withdrawn from a sandy layer.

One of the most common causes of fluid extraction–related subsidence is the over-pumping of groundwater from aquifers. If many wells are pumping water from the same aquifer the cones of depression surrounding each well begin to merge, lowering the regional groundwater level. Lowering of the groundwater table can lead to gradual, irreversible subsidence.

Surface subsidence associated with groundwater extraction is a serious problem in many parts of the southwestern United States and in coastal cities such as New Orleans. Many cities such as Tucson, Phoenix, Los Angeles, Salt Lake City, Las Vegas, and San Diego, rely heavily on groundwater pumped from compressible layers in underground aquifers.

The San Joaquin Valley of California offers a dramatic example of the effects of groundwater extraction. Extraction of groundwater for irrigation over a period of 50 years has resulted in nearly 30 feet (9 m) of surface subsidence. Parts of the Tucson Basin in Arizona are presently subsiding at an accelerating rate, and many investigators fear that the increasing rate of subsidence reflects a transition from temporary recoverable subsidence to a permanent compaction of the water-bearing layers at depth.

The world's most-famous subsiding city is Venice, Italy. Venice is sinking at a rate of about one foot per century. The city has subsided more than 10 feet since it was founded near sea level. Much of the city is below sea level or just above sea level and prone to floods from storm surges and astronomical high tides in the Adriatic Sea. These *acqua altas* (meaning high water in Italian) flood streets as far as the famous Piazza San Marco. Venice has been subsiding for a combination of reasons, including compaction of the coastal mud that the city was built on. One of the main causes of the sinking of Venice has been groundwater extraction. Nearly 20,000 groundwater wells pumped water from compressible sediment beneath the city, with the result being the city sank into the empty space created by the withdrawal of water. The Italian government has now built an aqueduct system to bring drinking water to residents, and has closed most of the 20,000 wells. This action has slowed the subsidence of the city, but it is still sinking, and this action may be too little too late to spare Venice from the future effects of storm surges and astronomical high tides.

Mexico City is also plagued with subsidence problems caused by groundwater extraction. Mexico City is built on a several-thousand-foot-thick sequence of sedimentary and volcanic rocks, including a large dried lake bed on the surface. Most of the groundwater is extracted from the upper 200 feet (60 m) of these sediments. Parts of Mexico City have subsided dramatically, whereas others have not. The northeast part of the city has subsided about 20 feet (6 m). Many of the subsidence patterns in Mexico City can be related to the underlying geology. In places like the northeast part of the city that are underlain by loose compressible sediments, the subsidence has been large. In other places underlain by volcanic rocks, the subsidence has been minor.

The extraction of oil, natural gas, and other fluids from the Earth also may result in surface subsidence. In the United States, subsidence related to petroleum extraction is a large problem in Texas, Louisiana, and parts of California. One of the worst cases of oil field subsidence is that of Long Beach, California, where the ground surface has subsided 30 feet (9 m) in response to extraction of underground oil. There are approximately 2,000 oil wells in Long Beach, pumping oil from beneath the city. Much of Long Beach's coastal area subsided below sea level, forcing the city to construct a series of dikes to keep the water out. When the subsidence problem was recognized and understood, the city began a program of reinjecting water into the oil field to replace the extracted fluids and to prevent further subsidence. This reinjection program was initiated in 1958, and since then the subsidence has stopped, but the land surface can not be pumped up again to its former levels.

Pumping of oil from an oil field west of Marina del Rey along the Newport-Inglewood fault resulted in subsidence beneath the Baldwin Hills Dam and Reservoir, leading to the dam's catastrophic failure on December 14, 1963. Oil extraction from the Inglewood oil field resulted in subsidence-related slip on a fault beneath the dam and reservoir, which was enough to initiate a crack in the dam foundation. The crack was quickly expanded by pressure from the water in the reservoir, which led to the dam's catastrophic failure at 3:38 P.M. on December 14, 1963. Sixty-five million gallons of water were suddenly released, destroying dozens of homes, killing five people, and causing $12 million in damage.

TECTONIC SUBSIDENCE

Plate tectonics is associated with subsidence of many types and scales, particularly on or near plate boundaries. Plate tectonics is associated with the large-scale vertical motions that uplift entire mountain ranges, drop basins to lower elevations, and form elongate depressions in the Earth's surface known as rifts that can be thousands of feet (km) deep. Plate tectonics also causes the broad flat coastal plains and passive margins to slowly subside relative to sea level, causing the sea to encroach slowly onto the continents. More local scale folding and faulting can cause areas of the land surface to rise or sink, although at rates that rarely exceed half an inch (1 cm) per year.

Extensional or divergent plate boundaries are naturally associated with subsidence, since these boundaries are places where the crust is being pulled apart, thinning, and sinking relative to sea level. Places where the continental crust has ruptured and is extending are known as continental rifts. In the United States, the Rio Grande rift in New Mexico represents a place where the crust has begun to rupture, and it is subsiding relative to surrounding mountain ranges. In this area, the actual subsidence does not present much of a hazard, since the land is not near the sea, and a large region is subsiding. The net effect is that the valley floor is slightly lower in elevation every year than it was the year before. The rifting and subsidence is sometimes associated with faulting when the basin floor suddenly drops, and the earthquakes are associated with their own sets of hazards. Rifting in the Rio Grande is also associated with the rise of a large body of magma beneath Socorro, and if this magma body has an eruption it is likely to be catastrophic.

The world's most extensive continental rift province is found in East Africa. An elongate subsiding rift depression extends from Ethiopia and Somalia in the north, south through Kenya, Uganda, Rwanda, Burundi, and Tanzania, then swings back toward the coast through Malawi and Mozambique. The East African rift system contains the oldest hominid fossils, and is also host to areas of rapid land surface subsidence. Earthquakes are common, as are volcanic eruptions such as the catastrophic eruption of Nyiragongo in Congo in January of 2002. Lava flows from Nyiragongo covered large parts of the town of Goma, forcing residents to flee to neighboring Rwanda.

Subsidence in the East African rift system has formed a series of very deep elongate lakes, including Lakes Edward, Albert, Kivu, Malawi, and Tanganyika. These lakes sit on narrow basin floors, bounded on their east and west sides by steep rift escarpments. The shoulders of the rifts slope away from the center of the rift, so sediments carried by streams do not enter the rift, but are carried away from it. This allows the rift lakes to become very deep without being filled by sediments. It also means that additional subsidence can cause parts of the rift floor to subside well below sea level, such as Lake Abe in the Awash depression in the Afar rift. This lake and several other areas near Djibouti rest hundreds of feet below sea level. These lakes, by virtue of being so deep, become stratified with respect to dissolved oxygen, methane, and other gases. Methane is locally extracted from these lakes for fuel, although periodic overturning of the lake's water can lead to hazardous release of gases.

When continental rifts continue to extend and subside, they eventually extend far enough that a young narrow ocean forms in the middle of the rift. An example of where a rift has evolved into such a young ocean is the Red Sea in the Middle East. The borders of the Red Sea are marked by large faults that down drop blocks of crust toward the center of the sea, and the blocks rotate and subside dramatically in this process. Most areas on the margin of the Red Sea are not heavily developed, but some areas, such as Sharm Al Sheikh on the southern tip of the Sinai Peninsula, have large resorts along the coast. These areas are prone to rapid subsidence by faulting and pose significant risks to the development in this and similar areas.

Transform plate boundaries, where one plate slides past another, can also be sites of hazardous subsidence. The strike-slip faults that comprise transform plate boundaries are rarely perfectly straight. Places where the faults bend may be sites of uplift of mountains, or rapid subsidence of narrow elongate basins. The orientation of the bend in the fault system determines whether the bend is associated with contraction and the formation of mountains or extension, subsidence, and the formation of the elongate basins known as pull-apart basins. Pull-apart basins typically subside quickly, have steep escarpments marked by active faults on at least two sides, and may have volcanic activity. Some of the topographically lowest places on Earth are in pull-apart basins, including the Salton Sea in California and the Dead Sea along the border between Israel and Jordan. The hazards in pull-apart basins are very much like those in continental rifts. An example of a transform boundary with coastal subsidence and uplift problems is found in southern California along the San Andreas fault. Many areas south of Los Angeles are characterized by faults that down-drop the coast because the faults have an extensional component along them. Further north, near Ventura and Santa Barbara, the San Andreas fault bends so that there is compression across the fault, and many areas along this segment of the coast are experiencing tectonic uplift instead of subsidence.

Convergent plate boundaries are known for tectonic uplift, although they may also be associated with regional subsidence. When a mountain range is pushed along a fault on top of a plate boundary, the underlying plate may subside rapidly. In most situations erosion of the overriding mountain range sheds enormous amounts of loose sediment onto the under-riding plate, so the land surface does not actually subside, although any particular marker surface will be buried and subside rapidly.

On March 27, 1964, southern Alaska was hit by a massive magnitude 9.2 earthquake that serves as an example of the vertical motions of coastal areas associated with a convergent margin. Ground displacements above the area that slipped were remarkable—much of the Prince William Sound and Kenai Peninsula area moved horizontally almost 65 feet (20 m), and moved upward by more than 35 feet (11.5 m). Other areas more landward of the uplifted zone were down dropped by several to 10 feet. Overall, almost 125,000 square miles (200,000 km^2) of land saw significant movements upward, downward, and laterally during this huge earthquake.

COMPACTION-RELATED SUBSIDENCE ON DELTAS AND PASSIVE MARGINS

Subsidence related to compaction and removal of water from sediments deposited on continental margin deltas, in lake beds, and in other wetlands poses a serious problem to residents trying to cope with the hazards of life at sea level in coastal environments. Deltas are especially prone to subsidence because the sediments that are deposited on deltas are very water-rich, and the weight of overlying new sediments compacts existing material, forcing the water out of pore spaces. Deltas are also constructed along continental shelves that are prone to regional-scale tectonic subsidence and are subject to additional subsidence forced by the weight of the sedimentary burden deposited on the entire margin. Continental margin deltas are rarely more than a few feet above sea level, so are prone to the effects of tides, storm surges, river floods, and other coastal disasters. Any decrease in the sediment supply to keep the land at sea level has serious ramifications, subjecting the area to subsidence below sea level.

Some of the world's thickest sedimentary deposits are formed in deltas on the continental shelves, and these are of considerable economic importance because they also host the world's largest petroleum reserves. The continental shelves are divided into many different sedimentary environments. Many of the sediments transported by rivers are deposited in estuaries, which are semi-enclosed bodies of water near the coast in which fresh water and seawater mix. Near-shore sediments deposited in estuaries include thick layers of mud, sand, and silt. Many estuaries are slowly subsiding, and they get filled with thick sedimentary deposits. Deltas are formed where streams and rivers meet the ocean and drop their loads because of the reduced flow velocity. Deltas are complex sedimentary systems, with coarse stream channels, fine-grained inter-channel sediments, and a gradation seaward to deepwater deposits of silt and mud.

All of the sediments deposited in the coastal environments tend to be water rich when deposited, and thus subject to water loss and compaction. Subsidence poses the greatest hazard on deltas, since these sediments tend to be thickest of all deposited on continental shelves. They are typically fine-grained mud and shale that suffer the greatest water loss and compaction. Unfortunately, deltas are also the sites of some of the world's largest cities, since they offer great river ports. New Orleans, Shanghai, and many other major cities have been built on delta deposits and have subsided 10 or more feet (several m) since they were first built. Many other cities built on these very compactable shelf sediments are also experiencing dangerous amounts of subsidence, as shown in the table "Subsidence Statistics for the 10 Worst-Case Coastal Cities" on page 726. The response to this subsidence will be costly. Some urban and government planners estimate that protecting the populace from sea level rise on subsiding coasts will be the costliest endeavor ever undertaken by humans.

The fate of these and other coastal cities that are plagued with natural and human-induced subsidence in a time of global sea level rise is subaqueous. The natural subsidence in these cities is accelerated by human activities. First of all, construction of tall heavy buildings on loose, compactable water-rich sediments forces water out of the pore spaces of the sediment underlying each building, causing that building to subside. The weight of cities has a cumulative effect, and big cities built on deltas and other compactable sediment cause a regional flow of water out of underlying sediments, leading to subsidence of the city as a whole.

New Orleans has one of the worst subsidence problems of coastal cities in the United States. Its rate and total amount of subsidence are not the highest,

SUBSIDENCE STATISTICS FOR THE 10 WORST-CASE COASTAL CITIES

City/State or Country	Maximum Subsidence	Area Affected	Tectonic Environment
	Feet (m)	*square miles (km^2)*	
Los Angeles (Long Beach), California	29.5 (9.0)	20 (50)	Oilfield subsidence
Tokyo, Japan	14.8 (4.5)	1,170 (3,000)	Delta
San Jose, California	12.8 (3.9)	312 (800)	Delta
Osaka, Japan	9.8 (3.0)	195 (500)	Delta
Houston, Texas	9.0 (2.7)	4,720 (12,100)	Oilfield and coastal marsh
Shanghai, China	8.6 (2.63)	47 (121)	Delta
Niigata, Japan	8.2 (2.5)	3,237 (8,300)	Delta
Nagoya, Japan	7.8 (2.37)	507 (1,300)	Delta
New Orleans, Louisiana	6.6 (2.0)	68 (175)	Delta
Taipei, Taiwan	6.2 (1.9)	51 (130)	

but since nearly half of the city is at or below sea level, any additional subsidence will put the city dangerously far below sea level. Already, the Mississippi River is higher than downtown streets, and ships float by at the second story level of buildings. Dikes keep the river at bay and usually keep storm surges from inundating the city. However, the catastrophes of Hurricanes Katrina and Rita in 2005, of Hurricane Camille in 1969, and many before this, show that the levees cannot be trusted to hold. Additional subsidence will make these measures unpractical, and lead to greater disasters than Hurricane Katrina. New Orleans, Houston, and other coastal cities have been accelerating their own sinking by withdrawing groundwater and oil from compactable sediments beneath the cities. They are literally pulling the ground out from under their own feet.

The combined effects of natural and human-induced subsidence with global sea level rise have resulted in increased urban flooding of many cities, and greater destruction during storms. Storm barriers have been built in some cases, but this is only the beginning. Thousands of miles of barriers will need to be built to protect these cities unless billions of people are willing to relocate to inland areas, an unlikely prospect.

Something must be done to reduce the risks from coastal subsidence. First, a more intelligent regulation of groundwater extraction from coastal aquifers, and oil from coastal regions, must be enforced. If oil is pumped out of an oil reservoir then water should be pumped back in to prevent subsidence. Sea level is rising, partly from natural astronomical effects and partly from human-induced changes to the atmosphere. It is not too early to start planning for sea level rises of a few feet (about 2 m). Sea walls should be designed and tested before given on massive scales. Consideration to moving many operations inland to higher ground should be given.

See also BASIN, SEDIMENTARY BASIN; DELTAS; GROUNDWATER; KARST; PASSIVE MARGIN; PLATE TECTONICS.

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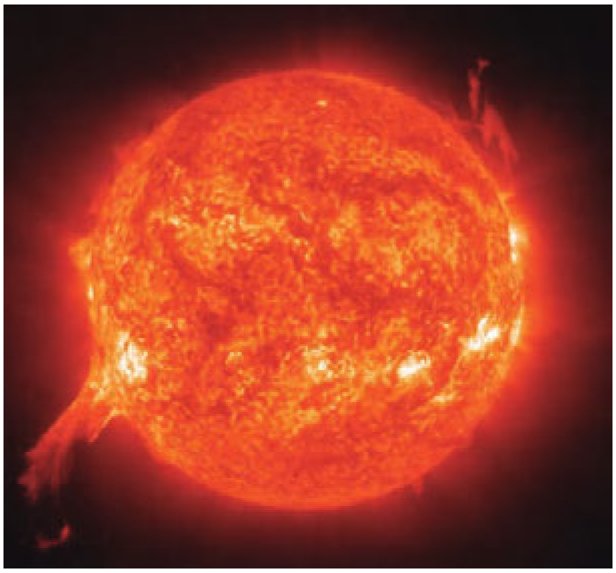
Sun The Sun is an average star that sits very close to Earth, a mere eight light minutes away, and 300,000 times closer than the next closest star, Alpha Centauri, which is located 4.3 light-years distant. It is a glowing ball of gas held together by its own gravity and powered by nuclear fusion in its core. Because of its proximity and fairly average characteristics,



Solar flare image taken by NASA's SOHO satellite, July 1, 2002 *(AP Images)*

the Sun has been extensively studied and forms the basis for many of the concepts and models about other stars in the universe. The Sun is also the only source of light and the main source of heat for life on Earth.

PHYSICAL PROPERTIES OF THE SUN

The Sun contains no solid material, but the apparent surface visible as a glowing solar disk is known as the photosphere. Above the photosphere is the Sun's lower atmosphere, called the chromosphere, and extending far past that is the corona, an outer atmosphere (visible during eclipses) that gradually merges into the solar wind and consists of particles that flow through the whole solar system. Extending below the photosphere toward the deep interior of the Sun are three more main zones. The region just below the photosphere is called the convection zone, where material is in constant motion. The solar interior has two main parts. The center of the Sun consists of the solar core, about 124,000 miles (200,000 km) in diameter, where nuclear fusion reactions burning hydrogen into helium power the entire Sun, generating light and heat for the whole solar system. Between the solar core and extending to the base of the convection zone is the radiation zone, a second interior zone, about 186,000 miles (300,000 km) thick, where the main heat transfer process is radiative.

The Sun has a diameter of 870,000 miles (1.4 million km) to the top of the photosphere, about 100 times the diameter of the Earth. The mass of the Sun is about 300,000 times that of Earth, approximately 4.3×10^{30} pounds (2.0×10^{30} kg). The table "Sun Reference Data" lists these and other basic properties of the Sun. The Sun rotates at different velocities at the poles and the equator, spinning faster at the equator than the poles in a manner similar to the gaseous Jovian planets. The temperature at the top of the photosphere is estimated to be 9,932°F (5,500°C).

One of the most important properties of the Sun is that it radiates energy into space, providing the energy to drive surface processes and provide conditions necessary for life on Earth. There are several ways to measure how much energy the Sun radiates. One way is to measure how much energy is received

SUN REFERENCE DATA

DIAMETER	870,000 miles (1.4 million km)	AGE	4.5 billion years
MASS	4.3×10^{30} pounds (2.0×10^{30} kg)	DISTANCE FROM EARTH	93 million miles (150 million km)
DENSITY	1.41 (relative to water being 1)	DISTANCE TO NEXT NEAREST STAR	4.3 light-years (Alpha Centauri)
SOLAR WIND SPEED	1,860,000 miles/hr (3 million km/hr)	LUMINOSITY	390 billion billion megawatts
SOLAR CYCLE	8–11 years	TEMPERATURE AT SURFACE	9,932°F (5,500°C)
TEMPERATURE AT CORE	22.5 million°F (14 million°C)	TEMPERATURE OF SUNSPOTS	7,232°F (4,000°C)
ROTATION PERIOD AT EQUATOR	27 Earth days	ROTATION PERIOD AT POLES	31 Earth days

in a specific area in a specific time. The solar constant is defined as how much solar energy reaches the Earth per unit time; its value is about 1,400 watts per 1.2 square yards (1 m^2). Solar luminosity is a measure of the total energy emitted by the Sun. It is defined as the total energy reaching an imaginary sphere with a radius of 1 astronomical unit (A.U., the distance from the Sun to the Earth). The Sun has a luminosity of 4×10^{26} watts. This is a huge amount of energy, equivalent to the energy released by 100 billion one-megaton nuclear bombs every second for the past several billion years.

THE INTERIOR OF THE SUN

Direct observation of the deep interior of the Sun is impossible, so most knowledge about the interior is based on computer modeling of remotely sensed surface phenomena. Observations have been grouped together to form what is known as the standard solar model.

One of the techniques of studying the solar interior is called helioseismology. This science studies complex patterns of pressure waves that alternately cause the surface of the photosphere to move up and down. These pressure waves then bounce off the undersurface of the photosphere and move through the interior. As the pressure waves interact they produce complex patterns on the surface that can be studied using techniques similar to earthquake seismology to yield information on the deep interior of the Sun. Much of the knowledge about the deep interior, including the density and temperature distributions, is based on analyses of these complex patterns.

Numerical models of the Sun predict that the zone beneath the photosphere is strongly convecting, as occurs in places where a cooler liquid overlies a warmer liquid. Convection evens out the temperature in the region where it occurs and is in agreement with the temperature distribution model based on helioseismology. The motion of gases transfers heat within this zone, flowing upward as warm currents and back down as cool currents; the gases then pick up more heat and flow upward once again. These currents form complex characteristic cell patterns that have many different scales and depths of overturning cells. These cells are tens of thousands of miles (km) in diameter 124,000 miles (200,000 km) below the surface, but only about 600 miles (1,000 km) across in the upper 600 miles (1,000 km) of the convection zone to the surface of the photosphere. The tops of these smaller convection cells form the visible surface of the Sun. Observations of these convection cells shows that they form a granular-looking surface, with many continent-sized light and dark patches that appear and disappear every 5–10 minutes. Spectroscopic observation of these granules shows that the bright patches are hot and moving upward, and the dark patches are colder and moving downward. The granules correspond to the tops of the convection cells, bringing the heat from the deep interior to the surface. A larger scale of granulation, forming supergranules, is superimposed on top of these granules.

Heat transfer beneath the convection zone occurs by radiation, a fundamentally different process. The gas in the deep interior above the core is completely ionized, and the high temperatures mean that the particles are moving quickly and encountering many collisions with each other. Nearly all atoms have been stripped of their electrons in the ionized medium, and photons produced by nuclear reactions in the core cannot be trapped by the atoms without electrons. Therefore, energy transfer in this zone is by the very efficient process of radiation. However, near the outer edge of the radiation zone in the interior, temperatures become progressively lower outward, and more and more atoms retain their electrons. This means that photons produced in the core begin to be absorbed in the outer part of the radiation zone. At a distance of about 124,000 miles (200,000 km) below the photosphere, the gas is almost totally opaque to photons, and by this distance, all of the photons produced by nuclear reactions in the core have been absorbed. The energy from these photons is then transferred as heat to the base of the convection zone, where it is transferred to the surface by convection. The photosphere, or surface of the Sun, is only about 300 miles (500 km) thick, so appears very sharp when viewed with telescopes.

SOLAR ATMOSPHERE

The lower part of the solar atmosphere, resting directly above the photosphere, is called the chromosphere. The chromosphere emits very little light compared to the photosphere, so is visible only during total solar eclipses, as a bright and somewhat irregular diffuse band around the Sun. The chromosphere has relatively few gas particles (hydrogen), so emits few photons. However, the chromosphere is a dynamic environment. Every few minutes the convection cells on the surface of the Sun emit spicules, storms of matter that shoot upward several thousand miles (km) into the upper atmosphere of the Sun at velocities of about 60 miles (100 km) per second. These spicules form mostly around the edges of the supergranules and may result from magnetic field interactions along the edges of the supergranules.

The corona is a diffuse zone outside the chromosphere, visible only during eclipses that block the photosphere as well as the chromosphere. Gases including hydrogen and iron in the corona are highly ionized (stripped of electrons) by the very high temperatures, which are higher than in the photosphere below. The temperature at the top of the photosphere is 6,000 K (10,340°F; 5,727°C), sinking to about 4,500 K (7,640°F; 4,227°C) in the chromosphere, rising through a transition zone out to 6,000 miles (10,000 km) into the corona where temperatures exceed 1,000,000 K (1,799,540°F; 999,727°C) out to distances well past 12,000 miles (20,000 km). The intense heating of the corona is probably caused by magnetic disturbances from the photosphere.

Fast-moving particles, including protons and electrons, and electromagnetic radiation are constantly moving away from the Sun at high velocity, forming the solar wind. The radiation travels at the speed of light but the physical particles move more slowly, at approximately 310 miles (500 km) per second, reaching the Earth a few days after they leave the Sun. The solar wind originates in the corona. About 6,000,000 miles (10,000,000 km) above the photosphere the temperatures are so high that the speed of the particles exceeds the escape velocity of the Sun's gravity, and material flows outward or evaporates in all directions into space. The material is constantly replaced from below, shedding about a million tons of matter each second. Remarkably, only 0.1 percent of the solar mass has been lost by this mechanism in the past 4.5 billion years. Most of the charged particles in the solar wind escape through areas of especially low density, called coronal holes. With less matter to interact with, the charged particles stream into space along magnetic field lines, reaching far into the solar system.

SUNSPOTS, FLARES, AND THE SOLAR CYCLE

The Sun produces a steady stream of electromagnetic radiation from the photosphere, essentially unchanging with time. Superimposed on this steady, quiet process are several dynamic, active, or changing events and cycles that show the Sun also has some unpredictable and explosive behavioral traits. These features are not significant in terms of total solar energy output but do influence the electromagnetic radiation received on Earth. They include sunspots, solar flares, magnetic storms, the solar cycle, and changes in the solar corona.

The surface of the Sun is covered by a number of dark spots, typically about the size of Earth (6,000 miles or 10,000 km across), that appear, disappear, and change in size and shape over periods of a day to 100 days. In detail they show a change in color from darkest in the center (called the umbra) to an intermediate color around the edges (penumbra) to merge with the photosphere on their edges. The colors correspond to changes in temperature, with the darkest regions representing a drop in temperature from 6,000 K (10,340°F; 5,727°C) on the photosphere, to 5,500 K (9,440°F; 5,227°C) in the penumbra, to 4,500 (7,640°F; 4,227°C) in the umbra.

Sunspots are intricately related to the magnetic field of the Sun. The magnetic field strength is measured to be about 1,000 times stronger in the sunspots than elsewhere on the photosphere. The strong magnetic field in these regions can block the normal convective flow from rising in these spots, explaining why they are cooler than their surroundings.

Sunspots typically occur in pairs, and the magnetic field has opposite polarity (positive or negative) in adjacent spots, with magnetic field lines looping out of one spot high into the solar atmosphere and into the other, forming a high-reaching arc in between. Another interesting observation is that at any time, all of the loops between sunspots have the same configuration in each hemisphere with respect to the rotation of the Sun. If the field lines loop from west to east in one pair, then all the other pairs in that hemisphere orient in the same direction, and all the pairs in the opposite hemisphere orient in the opposite direction. This phenomenon results from the differential rotation of the Sun. The different speeds of rotation between the poles and the equator cause the N-S magnetic axes to be distorted and sometimes reoriented to E-W, and the convection cells then distort these lines further forming the loops. These loops are occasionally so attenuated that they become shaped like narrow tubes which distort the convection cells and become manifested as sunspots.

The numbers and distributions of sunspots change in a regular fashion, a phenomenon known as the sunspot cycle. More than a century of observation shows that the number of spots peaks at about 100 per year every 11 years, and then decreases to about zero in between peaks. There is some variation in the cycle from 7–15 years, but it is a well-established cycle. Sunspots do not move in position, but during the course of a cycle, older spots at high latitudes are gradually replaced by more spots in more equatorial regions as the cycle reaches a climax every 11 years, with most spots appearing 15–20° from the equator. The solar minimum is when the spots are fewest in number, and the solar maximum is when most spots are observed, especially in equatorial regions. As the solar maximum grades into the next minimum, the highest latitude spots tend to disappear first, leaving the last few spots near the equator. As the next maximum approaches, the new spots will appear in high latitudes.

The sunspot cycle is complicated further by the fact that the entire magnetic field of the Sun reverses polarity every 11 years as part of a full 22-year cycle, so that the leading spots in both hemispheres switch from positive to negative, and negative to positive with each successive 11-year sunspot cycle. This cyclicity allows for a fairly regular interaction of the magnetic field with the convection in the outer layers of the Sun, in a manner similar to the generation of the Earth's geodynamo and magnetic field. The present 11-year cycle has not always been so regular, for instance, from the mid-1600s to the early 1700s, there were very few sunspots. This reflects the complex dynamics of the Sun's magnetic field and interaction with the convection system.

Although sunspots are dark, cool, and relatively inactive areas, they are sometimes surrounded by active regions that emit huge quantities of energetic particles into the surrounding corona. These active regions also follow the solar cycle and, like the sunspots, are most abundant and active during the solar maximum.

Solar prominences are giant loops or sheets of glowing ionized gas that erupt from the photosphere and move through the lower corona under the influence of the magnetic field, following the loops between two sunspots. They may be caused by magnetic instabilities near the sunspots where the magnetic field lines are extremely concentrated and unstable. At times their height reaches about half the solar diameter. Some prominences last for days or weeks in a fairly stable configuration, whereas others surge and disappear in a matter of hours.

Active regions also release highly energetic flares that erupt and move around on the surface near the active regions, releasing huge amounts of energy, especially in the X-ray and ultraviolet wavelengths. Temperatures in the cores of flares can exceed 10,000,000 K (17,999,540°F; 9,999,726°C), and the amount of energy released in these flares in a few minutes can exceed that from the larger prominences over a period of weeks. The particles released in the flares are so energetic that they escape the Sun's gravity and are blasted into space where they disrupt communications and other electronics.

The sunspot cycle also affects the solar corona, which is smooth and uniform during solar minimums, and irregular, much larger, and contains many beams or streamers moving away from the Sun at solar maximums. The corona may be heated mostly by flares and prominences; during periods of more activity the corona becomes more active as well, and the solar wind increases.

SOLAR CORE

The energy from the Sun comes from nuclear reactions in its core, generating a luminosity of 4×10^{26} W, or 2×10^4 W/kg. The Sun has been producing approximately this vast amount of energy for the past 4.5 billion years. For the entire lifetime of the Sun, the total amount of energy generated has been 3×10^{13} joule/kg. The generation of this energy has been remarkably steady and is expected to continue for another 5 billion years, through the process of nuclear fusion.

Fusion works by combining two atomic nuclei to form one and releases energy according to the law of conservation of mass and energy. During fusion reactions, mass is lost but is converted to energy according to Einstein's equation

$$E = mc^2$$

where E = energy, m = mass, and c = the speed of light.

During nuclear fusion the total amount of mass and energy is conserved, but the mass is gradually converted to energy, which is the energy that has been emitted from the Sun for the past 4.5 billion years. Nuclear energy is generated by fusion along a reaction series called the proton-proton chain. Positively charged atomic nuclei naturally repel each other, but if they collide at very high speeds (such as generated by high temperatures in the core of the Sun) then they can overcome the repulsive forces between the nuclei and then be influenced by a different force called the strong nuclear force. This force, which acts at distances smaller than 10^{-15} m, can bind the two positively charged nuclei together, releasing energy in the process. Temperatures in excess of 10^7 K are needed to generate the speeds that cause this nuclear fusion.

When the two nuclei of hydrogen (protons) interact in the fusion reaction, they produce a new proton, a neutron, a positron, and a neutrino. The positron has the same properties as an electron except that it has a positive charge, and it is classified as an antiparticle of an electron, or as antimatter. When the fusion reaction occurs and the positron is formed, it is immediately released into a sea of free electrons in the solar core. When matter and antimatter particles meet they violently annihilate each other and release energy in the form of gamma rays.

The other particle released in the fusion reaction is a neutrino, a particle with no charge and a mass so low that it is approximately equal to about 1/10,000 that of an electron. They move at nearly the speed of light and are nearly (but not quite) impossible to detect since they can penetrate anything, even a wall of lead several light-years thick.

The proton and neutron produced in the fusion reaction merge to form a deuteron, which is the nucleus of deuterium or heavy hydrogen. It is called "heavy" since it has an extra neutron relative to the most common form of hydrogen, which lacks a neutron. Nuclei that have the same number of protons but different numbers of neutrons are known as isotopes of the same element, and deuterium is an isotope of hydrogen. The isotopic number is written as a prefix to the element symbol in standard notation. Thus, the hydrogen fusion reaction that powers the Sun can be written as

$$^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + \text{positron} + \text{neutrino}$$

This reaction is only the first in the proton-proton chain that powers the Sun, followed quickly by the formation of helium (He) by the interaction of deuterium with an isotope of helium according to the following equation:

$$^{2}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \text{energy (gamma ray photons)}$$

Next, helium 4 is produced by the fusion of two helium 3 isotopes according to the following equation:

$$^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{H} + {}^{1}\mathrm{H} \\ + \text{energy (gamma ray photons)}$$

The net effect of the proton-proton reaction chain is that four hydrogen nuclei are fused into one helium 4 isotope plus two neutrinos, releasing a large amount of energy in the form of gamma rays. As the gamma ray photons move through the Sun they slowly lose energy as it is absorbed by ions and electrons, getting converted to heat by the convecting layer and then is emitted at the photosphere in the form of visible light that is observed from Earth. The helium remains in the core of the Sun, and the neutrinos escape at close to the speed of light.

Calculations of the mass to energy conversion show that about 600 million tons of hydrogen have been fused into helium in the core of the Sun every second for the past several billion years.

See also ASTRONOMY; ASTROPHYSICS; AURORA, AURORA BOREALIS, AURORA AUSTRALIS; COSMIC RAYS; GREENHOUSE EFFECT; ORIGIN AND EVOLUTION OF THE EARTH AND SOLAR SYSTEM; SOLAR SYSTEM; STAR FORMATION; STELLAR EVOLUTION; SUN HALOS, SUNDOGS, AND SUN PILLARS.

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sun halos, sundogs, and sun pillars A number of unusual phenomena are related to the interaction of the Sun's rays with ice crystals in the upper atmosphere. A ring of light that circles and extends outward from the Sun, or the Moon, is known as a halo. The halo forms when ice crystals in high-level cirriform clouds refract the Sun's or Moon's rays. Most sun halos form at an angle of 22° from the Sun because randomly oriented small ice particles refract the light at this angle. Occasionally a 46° halo is visible, formed when subhorizontally oriented columnar ice crystals refract the light at this higher angle. Most sun halos are simply bright bands of light but some exhibit rainbowlike zones of color. These form when the light is dispersed by the ice crystals and light of different wavelengths (colors) is refracted by different amounts depending on its speed

Atmospheric crystals sometimes cause hexagonal or platy ice crystals to fall slowly through the atmosphere, and this vertical motion causes the crystals to become uniformly oriented with their long dimensions in a horizontal direction. This orientation prevents light that is refracted through the ice crystals from forming a halo, but when the Sun approaches the horizon it causes two bright spots or colored bright spots to appear on either side of the sun. These spots are commonly called sundogs, or parhelia.

Sun pillars are a similar phenomenon but are formed by light that is reflected off the ice crystals instead of refracted through them. In this case, usually at sunset or sunrise, the Sun's rays reflect off the subhorizontally oriented ice crystals and form a long column of light extending downward from the Sun.

Rainbows are a somewhat related phenomena. Rainbows are translucent concentric arcs of colored bands that are visible in the air under certain conditions when rain or mist is present in the air and the Sun is at the observer's back. Rainbows form where sunlight enters the rain or water drops in the air, and a small portion of this light is reflected off the back of the raindrops and directed back to the observer. When the sunlight enters the rain drops, it is bent and slows, and as in a prism, violet light is refracted the most and red the least. The amount of light that is reflected off the back of each raindrop is small compared to the amount that enters each drop, and only the rays that hit the back of the drop at angles greater than the critical angle are reflected. Since the sun's rays are refracted and split by color when they enter the water drops, each color hits the back of the raindrop at a slightly different angle, and the reflected light emerges from the raindrop at different angles for each color. Red light emerges at 42° from the incoming beam, whereas violet light emerges at 40°. An observer sees only one color from each drop, but with millions of drops in the sky an observer is able to see a range of colors formed from different raindrops with light reflected at slightly different angles to the observer. Rainbows appear to move as an observer moves, since each ray of light is entering the observer's eyes from a single raindrop, and as the observer moves, light from different drops enters the observer's eyes.

See also ATMOSPHERE; SUN.

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supercontinent cycles Supercontinent cycles are semiregular groupings of the planet's landmasses into single or large continents that remain stable for a period of time, then disperse, and eventually come back together as new amalgamated landmasses with a different distribution. At several times in Earth history, the continents have joined together forming one large supercontinent, with the last supercontinent, Pangaea (meaning all land), breaking up approximately 160 million years ago. This process of supercontinent formation, dispersal, and reamalgamation seems to be grossly cyclic, perhaps reflecting mantle convection patterns, but also influencing climate and biological evolution. Early investigators noted global "peaks" in age distributions of igneous and metamorphic rocks and suggested that these represent global orogenic or mountain building episodes, related to supercontinent amalgamation.

The basic idea of the supercontinent cycle is that continents drift about on the surface until they all collide, stay together, and come to rest relative to the mantle in a place where the gravitational potential surface (geoid) has a global low. The continents are only one-half as efficient at conducting heat as oceans, so after the continents are joined together, heat accumulates at their base, causing doming and breakup of the continent. For small continents, heat can flow sideways and not heat up the base of the plate, but for large continents the lateral distance is too great for the heat to be transported sideways. The heat rising from within the Earth therefore breaks up the supercontinent after a heating period of several tens or hundreds of millions of years. The heat then disperses and is transferred to the ocean/atmosphere system, and continents move apart until they come back together to form a new supercontinent.

The supercontinent cycle greatly affects other Earth systems. The breakup of continents causes sudden bursts of heat release, associated with periods of increased, intense magmatism. It also explains some of the large-scale sea level changes, episodes of rapid and widespread orogeny, episodes of glaciation, and many of the changes in life on Earth.

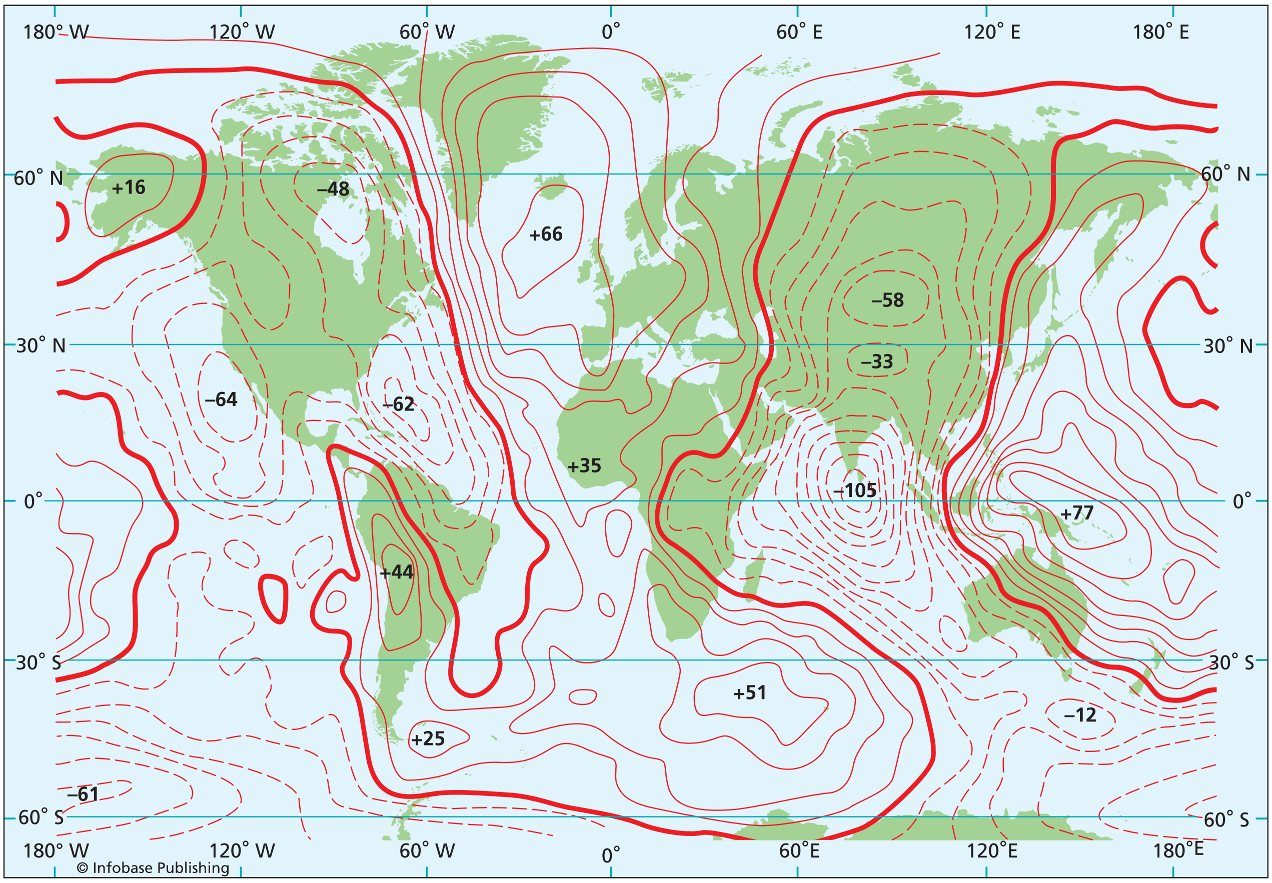
Compilations of Precambrian isotopic ages of metamorphism and tectonic activity suggest that the Earth experiences a periodicity of global orogeny of 400 million years. Peaks have been noted at time periods including 3.5, 3.1, 2.9, 2.6, 2.1, 1.8, 1.6, and 1.1 billion years ago, as well as at 650 and 250 million years ago. One hundred million years after these periods of convergent tectonism and metamorphism, rifting is common and widespread. Geologist A. H. Sutton (1963) proposed the term *chelogenic cycle,* in which continents assemble and desegregate in antipodal supercontinents.

RELATIONSHIP OF SUPERCONTINENTS, LOWER MANTLE CONVECTION, AND THE GEOID

Some models for the formation and dispersal of supercontinents suggest a link between mantle convection, heat flow, and the supercontinent cycle. Stationary supercontinents insulate the mantle, causing it to heat up, because the cooling effects of subduction and seafloor spreading are absent. As the mantle then heats up, convective upwelling is initiated, causing dynamic and isostatic uplift of the continent, injection of melts into the continental crust, and extensive crustal melting. These crustal melts are widespread in the interiors of some reconstructed supercontinents, such as the Proterozoic anorogenic granites in interior North America, which were situated in the center of the supercontinent of Rodinia when they formed between 1 billion and 800 million years ago.

After intrusion of the anorogenic magmas, the lithosphere is weakened and can be more easily driven apart by divergent flow in the asthenosphere. Thermal effects in the lower mantle lag behind surface motions. So, the present Atlantic geoid high and associated hot spots represent a "memory" of heating beneath Pangaea. Likewise, the circum Pangaea subduction zones may have memory in a global ring of geoid lows.

Other models for relationships between supercontinents and mantle convection suggest that super-



The geoid is an imaginary surface that would be sea level if it extended through the continents. The geoid surface is perpendicular to the gravity plumb lines at every location.

continents result from mantle convection patterns. Continental fragments may be swept toward convective downwellings, where they reaggregate as supercontinents.

PLATE TECTONICS, SUPERCONTINENTS, AND LIFE

Plate tectonic motions, especially the supercontinent cycle, profoundly affect the distribution and evolution of life on Earth. Plate tectonic activity such as rifting, continental collision, and drifting continents affects the distribution of life-forms, the formation and destruction of ecological niches, and radiation and extinction blooms. Plate tectonic effects also can induce sea level changes, initiate periods of global glaciation, change the global climate from hothouse to icehouse conditions, and affect seawater salinity and nutrient supply. All of these consequences of plate tectonics profoundly influence life on Earth.

Changes in latitude brought on by continental drift bring land areas into latitudes with better or worse climate conditions. This has different consequences for different organisms, depending on their temperature tolerance, as well as food availability in their environment. Biological diversity generally increases toward the equator, so, in general, as continents drift poleward more organisms tend to go extinct, and as they drift equatorward, diversification increases.

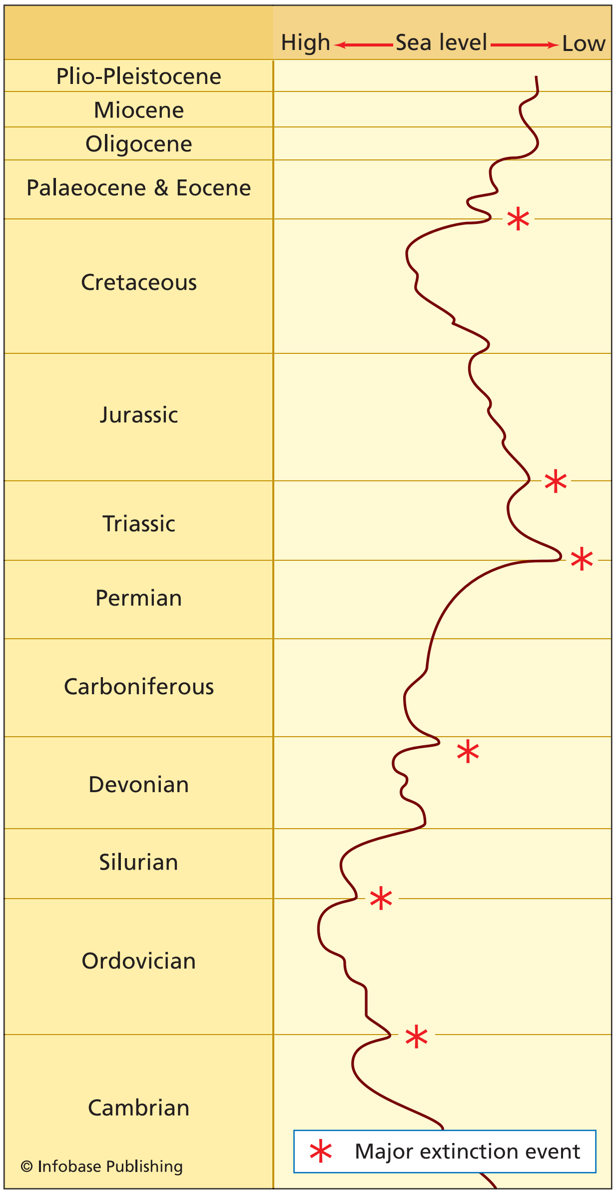
Tectonics and supercontinent dispersal break apart and separate faunal provinces, which then evolve separately. Continental collisions and supercontinent amalgamation build barriers to migration but eventually bring isolated fauna together. One of the biggest mass extinctions (at the end of the Permian) occurred with the formation of a supercontinent (Pangaea), sea level regression, evaporite formation, and global warming. At the boundary between the Permian and Triassic Periods and between the Paleozoic and Mesozoic Periods (250 million years ago), 70–90 percent of all species became extinct. Casualties included the rugose corals, trilobites, many types of brachiopods, and marine organisms including many foraminifer species.

The Siberian flood basalts cover a large area of the central Siberian Plateau northwest of Lake Baikal. They are more than one-half mile thick over an area of 210,000 square miles (547,000 km^2) but have significantly eroded from an estimated volume of 1,240,000 cubic miles (3,3133,000 km^3). They were erupted over a period of less than 1 million years, 250 million years ago at the end of the Permian at the Permian-Triassic boundary. They are remarkably coincident in time with the major Permian-Triassic extinction, implying a causal link. The Permian-Triassic boundary at 250 million years ago marks the greatest extinction in Earth history, where 90 percent of marine species and 70 percent of terrestrial vertebrates became extinct. The rapid volcanism and degassing could have released enough sulfur dioxide to cause a rapid global cooling, inducing a short ice age with associated rapid fall of sea level. Soon after the ice age took hold, the effects of the carbon dioxide that was also emitted by the volcanism took over and the atmosphere heated, resulting in a global warming. The rapidly fluctuating climate postulated to have been caused by the volcanic gases is thought to have killed off many organisms, which were simply unable to cope with the wild climate changes.

Continental breakup can physically isolate species that cannot swim or fly between the diverging continents. Physical isolation (via tectonics) produces adaptive radiation—continental dispersal thus increases biotic diversity. Mammals had an explosive radiation (in 10–20 million years) in the Paleocene-Eocene, right after breakup of Pangaea.

SEA LEVEL CHANGES, SUPERCONTINENTS, AND LIFE

Sea level has changed by about a thousand feet (hundreds of meters) above and below current levels many times in Earth history. In fact, sea level constantly changes in response to a number of different variables, many of them related to plate tectonics. The diversity of fauna on the globe closely relates to sea levels, with greater diversity during sea level high stands, and lower diversity during sea level lows. For instance, sea level was 1,970 feet (600 m) higher than now during the Ordovician, and the sea level high stand was associated with a biotic explosion. Sea levels reached a low stand at the end of the Permian, and this low was associated with a great mass extinction. Sea levels rose again in the Cretaceous.



Sea level has risen and fallen dramatically through Earth history. Global sea level rise and fall must be separated from local subsidence and uplift events along individual coastlines, by correlating events between different continents. Global eustatic sea level curves (Vail curves) also show the height of the world's oceans after local effects have been removed.

Sea levels change at different rates and amounts in response to changes in several other Earth systems. Local tectonic effects may mimic sea level changes through regional subsidence or uplift, and these effects must be taken into account and filtered out when trying to deduce ancient, global (eustatic) sea level changes. The global volume of the mid-ocean ridges can change dramatically, either by increasing the total length of ridges or changing the rate of seafloor spreading. The total length of ridges typically increases during continental breakup, since continents are being rifted apart and some continental rifts can evolve into mid-ocean ridges. Additionally, if seafloor spreading rates are increased, the amount of young, topographically elevated ridges is increased relative to the slower, older, topographically lower ridges that occupy a smaller volume. If the volume of the ridges increases by either mechanism, then a volume of water equal to the increased ridge volume is displaced and sea level rises, inundating the continents. Changes in ridge volume are able to change sea levels positively or negatively by about 985 feet (300 m) from present values, at rates of about 0.4 inch (1 cm) every 1,000 years.

Continent-continent collisions, such as those associated with supercontinent formation, can lower sea levels by reducing the area of the continents. When continents collide, mountains and plateaus are uplifted, and the amount of material that is taken from below sea level to higher elevations no longer displaces seawater, causing sea levels to drop. The contemporaneous India-Asia collision has caused sea levels to drop by 33 feet (10 m).

Other factors such as mid-plate volcanism can also change sea levels. The Hawaiian Islands are hot-spot style, mid-plate volcanoes that have been erupted onto the seafloor, displacing an amount of water equal to their volume. Although this effect is not large at present, at some periods in Earth history many more hot spots existed (such as in the Cretaceous), and the effect would have been larger.

The effects of the supercontinent cycle on sea level may be summarized as follows: Continent assembly favors regression, whereas continental fragmentation and dispersal favors transgression. Regressions followed formation of the supercontinents of Rodinia and Pangaea, whereas transgressions followed the fragmentation of Rodinia and the Jurassic-Cretaceous breakup of Pangaea.

EFFECTS OF TRANSGRESSIONS AND REGRESSIONS

During sea level transgressions, continental shelves are covered by water, and available habitats are enlarged, increasing the diversity of fauna. Transgressions are generally associated with greater diversification of species. Regressions cause extinctions through loss of environments, both shallow marine and beach. There is a close association between Phanerozoic extinctions and sea level low stands. Salinity fluctuations also affect diversity—the formation of evaporites (during supercontinent dispersal) causes reduction in oceanic salinity. For instance, Permian-Triassic rifts formed during the breakup of Pangaea had lots of evaporites (up to 4.4 miles, or 7 km thick), which lowered the salinity of oceans.

Supercontinents affect the supply of nutrients to the oceans, and thus, the ability of life to proliferate. Large supercontinents cause increased seasonality, and thus lead to an increase in the nutrient supply through overturning of the ocean waters. During breakup and dispersal, smaller continents have less seasonality, yielding decreased vertical mixing, leaving fewer nutrients in shelf waters. Seafloor spreading also increases the nutrient supply to the ocean; the more active the seafloor spreading system, the more interaction there is between ocean waters and crustal minerals that get dissolved to form nutrients in the seawater.

See also GREENHOUSE EFFECT; ICE AGES; PLATE TECTONICS.

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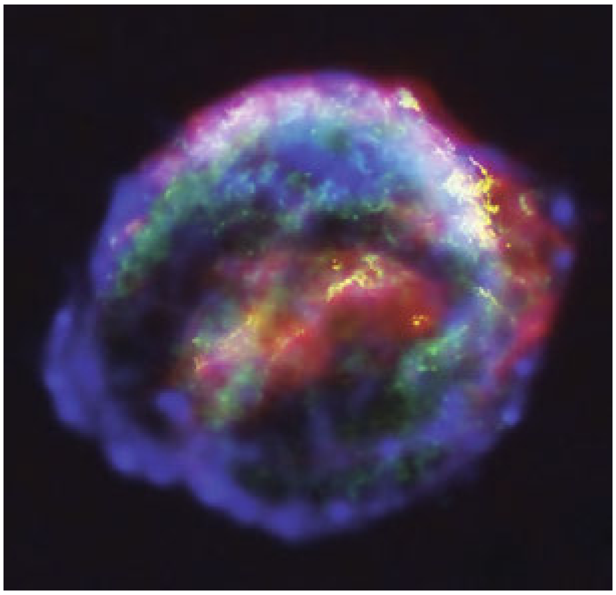
supernova Supernovas are extremely luminous stellar explosions associated with large bursts of radiation that can exceed the brightness of the entire galaxy it is associated with for a period of weeks or months. The energy released in a supernova event can exceed the amount of energy produced by the Earth’s Sun over its entire life span. In these stellar explosions material is expelled from the core star at speeds of about one-10th the speed of light and is associated with a shock wave that moves through the interstellar medium, sweeping up an expanding shell of gas and dust that is known as a supernova remnant. A nova is a general name for a type of star that vastly increases in brightness (by up to 10,000 times) over very short periods of time, typically weeks. The word *nova* comes from the Latin for “new” and stems from early astronomers who thought that nova were new stars appearing in the sky, since the parent stars were too faint to be observed from the Earth before powerful telescopes were invented. The term *nova* is used for any star that increases rapidly in brightness by ejecting some of its material in the form of a cloud, whereas supernova are associated with stellar explosions, and are much more, even millions of times as luminous and energetic as nova.

Several different types of supernovas have been identified. The most common type is produced when a massive star ages and stops generating energy from nuclear fusion because it has spent all of its fuel. The massive star can undergo sudden gravitational collapse to form a neutron star or black hole, releasing



Kepler's supernova taken from combined data from *Hubble Telescope, Spitzer Telescope,* and *Chandra X-Ray Observatory* *(NASA Marshall Space Flight Center)*

huge amounts of gravitational potential energy that heats up and then expels the star's outer layers. A second type of supernova forms when a white dwarf star accumulates enough material from a stellar companion, typically in a binary star system, to raise the core temperature enough to start fusion of carbon, which forms a runaway nuclear fusion reaction, causing the star to explode. This may happen after the white dwarf has gone through hundreds of smaller nova events, each time exploding away an outer shell of gas, but leaving some behind that eventually contributes to the final, death-blow supernova explosion of the entire star.

A supernova event occurs about once every 50 years in the Milky Way Galaxy and other galaxies of similar size. The expanding shock waves from supernovas play an important role in synthesizing heavier elements and in triggering the formation of new stars.

DEATH OF HIGH-MASS STARS

High-mass stars containing more than eight solar masses have a very different evolution from low mass stars and have an explosive death that is responsible for forming many of the heavier elements in the universe.

Evolved high-mass stars have a core with concentric zones of progressively heavier fuel, with the burnt "ash" of one layer forming the fuel for the next deeper layer in the star. At the edge of the core, hydrogen burns to fuse helium, then helium burns to fuse into carbon, which fuses into oxygen. The oxygen goes through nuclear fusion to form neon, which then forms magnesium, then silicon, and then iron nuclei ash in the core of the massive star. As each fuel is used up, the core of the star contracts, heats up, then starts to burn the fuel of the ash of the previous episode of burning. Each successive burning stage is hotter, proceeds faster than the one before, and lasts for a much shorter time. A typical massive star that is about 20 solar masses may burn hydrogen for 10 million years, helium for 1 million years, carbon 1,000 years, oxygen for 1 year, silicon for a week, and iron for less than one day. After this the core of the massive star collapses, and one of the universe's most spectacular events unfolds.

CORE COLLAPSE IN GIANT STARS

When iron is produced in the core of the massive star, the internal processes suddenly change. The iron is so dense, consisting of 26 protons and 30 neutrons, that when it burns no energy can be extracted by combining this to make heavier elements. The result is that when significant quantities of iron accumulate in the core the internal fires suddenly are extinguished, and the equilibrium of the star is destroyed. The temperature in the core is several billion K, but without continued nuclear fusion the force of gravity at this stage begins to overwhelm the outward gas pressure and the star begins a fateful collapse and implosion.

As the star begins to collapse the core temperature shoots up to about 10 billion K, and the photons take on a high energy state, splitting the iron into lighter nuclei, quickly breaking down the elements in a process called photodisintegration so that only protons and neutrons remain. In less than one second all of the heavy elements produced by nuclear fusion in the entire core of the star have broken down into simple protons and neutrons, undoing 10 million years of nuclear reactions. Photodisintegration requires a huge amount of energy from the high-temperature core and transferring this energy from the core to break down these elements cools the core, which reduces the outward fluid pressure that is resisting the inward pull of gravity. The sudden loss of pressure in the core causes the collapse of the core of the star to accelerate rapidly.

As the core continues to shrink, the pressures on the mixture of free electrons, protons, neutrons, and photons, and the rapidly rising pressures crush the protons and electrons together to form neutrons and neutrinos in a process called neutronization. Neutrinos are such high-energy particles that they rarely interact with matter, even matter as dense as that in the core of the collapsing giant star. Most of the neutrinos therefore pass right through the core and escape to space carrying large amounts of energy with them. At this stage the core finds itself in a state where the electrons and neutrinos have escaped, so that the neutrons in the core are coming into contact with each other, at a super high density of 10^{15} kg/m^3. At this high density the neutrons influence and oppose each other with a very strong force, generating strong pressure called the neutron degeneracy pressure, which acts against the inward pull of gravity. By the time this force is able to oppose the ongoing rapid gravitational collapse of the star, however, the core has gone beyond its point of equilibrium and has reached densities between 10^{17} to 10^{18} kg/m^3. These forces interact; the rapid gravitational collapse hits the super-dense neutron mass in the core with the strong neutron degeneracy pressure, and the inward collapse bounces backward to produce a rapid expansion. The total time elapsed from the start of the collapse of the core to the beginning of the outward expansion is less than one second. The outward expansion is associated with a tremendously powerful shock wave that moves outward through the star, blasting all of the star's outer layers into space in one of the most powerful events known in the universe, a supernova. These outer layers contain many heavy elements around the core, as well as light elements near the surface, and as the star explodes these are all blown into interstellar space in a bright flash that may last only a few days at its peak. Supernovas are among the brightest events known in the universe, being about a million times brighter than novas, and often being about the same brightness—for a few days—as a galaxy with a trillion stars. The supernova may have an initial flash that is more than a billion times brighter than the Earth's Sun and produces more energy over the time from its initial flash until it completely fades away a few months later than the Sun produces in its entire history.

DIFFERENT TYPES OF SUPERNOVAS

Enough supernovas have been observed to characterize some differences between them. Some supernovas have very little hydrogen associated with them (called Type-I supernovas), whereas others are hydrogen-rich (Type-II supernovas) and are associated with the star collapse or implosion described above. These two types of supernovas that have observationally different luminosity vs. time curves also have fundamentally different origins.

A Type-I supernova, also known as a carbon-detonation supernova, is produced from a white dwarf star that has gone through a number of nova events after accreting hydrogen and helium from a companion main sequence star and then burning the hydrogen to form helium. In some white dwarf binary star systems, each nova does not expel all of the accreted helium from around the core of the white dwarf, and eventually this builds up to a critical mass, at which point the star becomes unstable because the gravitational force exceeds the electron degeneracy force in the core, causing it to collapse and explode for a final time in a supernova. The mass at which a white dwarf binary system becomes unstable has been calculated to be about 1.4 solar masses, by Indian astronomer (and Nobel Laureate) Subramanyan Chandrasekhar, and is known as the Chandrasekhar mass. These supernovas are hydrogen-poor because there is very little hydrogen in the system when it explodes.

During the collapse of such a white dwarf to form a Type-I supernova, the star heats up to the point at which carbon begins to fuse into heavier elements almost everywhere throughout the star at the same time, causing the star to explode in a massive carbon-detonation explosion that is comparable in violence to the Type-II supernova formed by the implosion of very massive stars. Type-I or carbon-detonation supernovas may also be caused by two white dwarf stars in a binary system that collide to form a massive unstable star that explodes in a supernova.

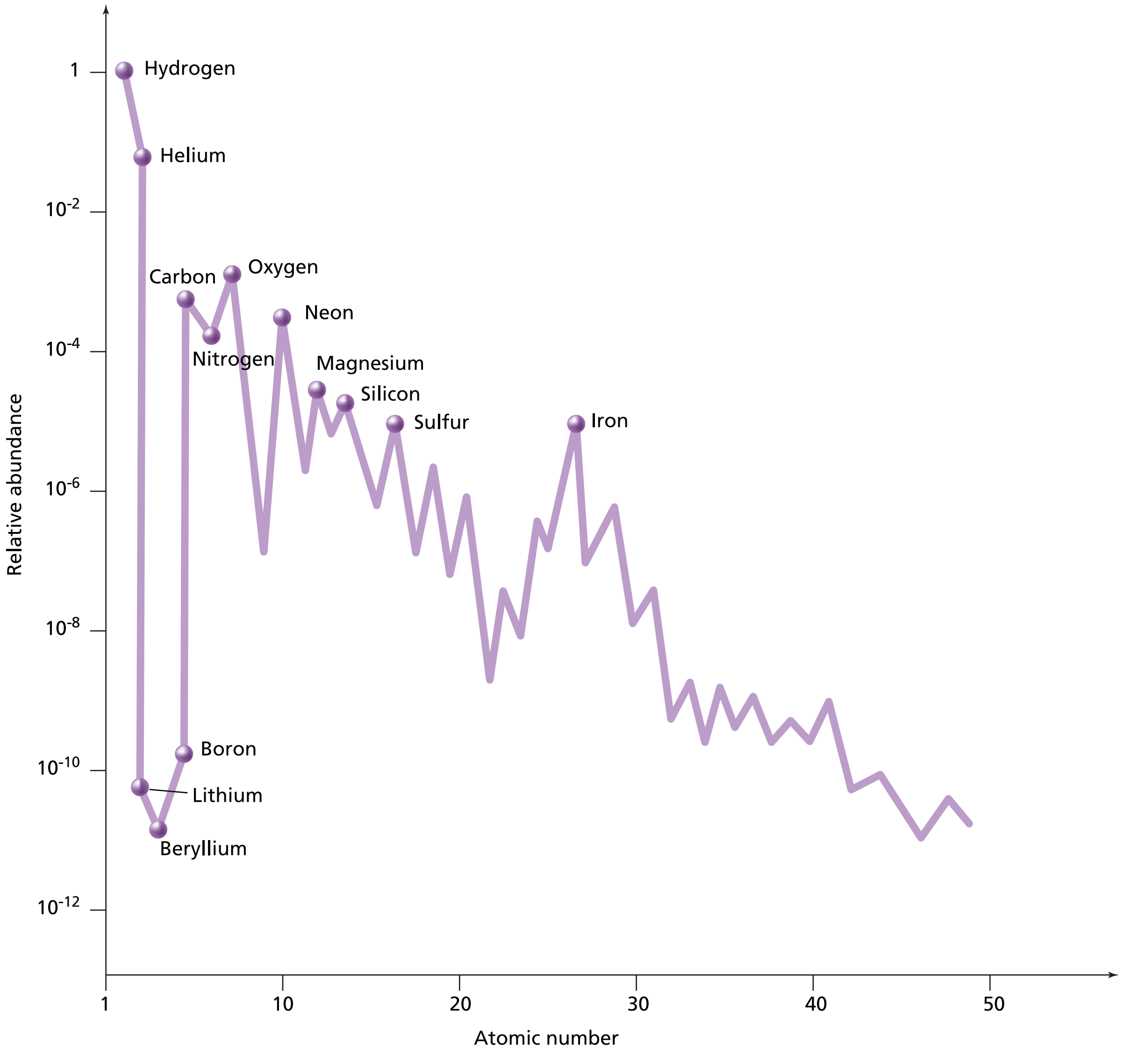
SUPERNOVA REMNANTS

Supernovas are observed only about every hundred years from Earth, but many supernova remnants are still observable long after their peak of luminosity and radiance. The most famous of these is the Crab Nebula, now a dim nebula sitting about 5,940 light-years (1,800 parsecs) from the Earth and having a visible angular diameter about one-fifth that of the Moon. The Crab Nebula is so interesting because in 1054 its initial explosion was recorded by Chinese, Native American, and Middle Eastern astronomers, who recorded its brightness to be greater than Venus and rivaling the Moon. The explosion was so bright that it was visible in broad daylight for about one month, and the material is still moving outward from the central region at a couple of thousand miles per second (several thousand km/sec). Another historically famous supernova is Tycho's supernova, named after Danish nobleman and astronomer Tycho Brahe (1546–1601). It caused a sensation throughout the world during the Renaissance, causing many people to abandon existing ideas that the universe was constant and nonchanging.

SUPERNOVAS AND THE FORMATION OF THE HEAVY ELEMENTS

Supernovas are fundamentally important for life and the state of the universe, since nearly all of the elements heavier than carbon are formed in massive stars, and the elements heavier than bismuth 209 are all formed in supernova explosions. Only the elements hydrogen and helium are primordial in the universe, meaning that they have been in existence since the earliest moments of the universe. All of the other elements have been produced by nucleosynthesis, or the combination of large atomic nuclei from smaller ones, in stars and in more energetic events such as supernovas.

Heavy elements are created by successive nuclear fusion reactions, beginning with the fusion of two hydrogen atoms to form helium; then helium can fuse to carbon in some star cores. The temperature in very massive stars can be high enough to fuse carbon into magnesium, but it is very rare to synthesize any elements that require the fusion of two nuclei larger than carbon because the nuclear forces between the protons become prohibitively large with larger atomic nuclei. Production of heavier elements typically happens by a different process—the capture of a helium atom by a larger atomic nucleus—to produce heavier elements. In this way, a carbon 12 nucleus can collide with a helium 4 nucleus to produce oxygen 16, and oxygen 16 can collide with helium 4 to produce neon 20. The process of helium capture is thought to have produced many of the heavier elements in the universe, because a plot of the abundance of the elements shows that elements with nuclear masses of 4 units (helium), 12 units (carbon), 16 units (oxygen),



Plot of cosmic abundance of elements and their isotopes expressed relative to the abundance of hydrogen. The horizontal axis shows atomic number. Note how many of the common elements are located on peaks, with other elements being tens to hundreds of times less abundant. The elements on the peaks (e.g., iron) were produced in stellar nucleosynthesis.

20 units (neon), 24 units (magnesium), and 28 units (silicon) stand out as prominent peaks. The process continues in large-mass stars with sulfur 32, argon 36, calcium 40, titanium 44, chromium 48, iron 52, and nickel 56. However, nickel 56 is unstable and quickly decays into cobalt 56, then iron 56, which is a very stable nucleus (the most stable of all nuclei), consisting of 26 protons and 30 neutrons. This process therefore inevitably leads to the buildup of stable iron in the core of massive stars. Many other nuclear reactions occur in large evolved stars, but the plot of the relative abundance of the elements shows that helium capture is one of the most important in synthesizing the heavier elements.

A different process is needed to make elements heavier than iron. This process, called the slow, or s-process by astronomers, involves the capture and absorption of neutrons by other nuclei. Neutron capture occurs in the cores of large evolved stars, where the nuclei of iron atoms capture some of the neutrons produced as by-products of the nuclear reactions going on in the core. The process of adding neutrons to an atomic nucleus changes the isotope of that element to a heavier isotope, but it is still the same element. At some point, however, there are so many neutrons that the isotope decays radioactively to produce a nucleus of a new element. For instance, iron 56 will add neutrons and become iron 59, which will decay to cobalt 59. Cobalt 59 will then add neutrons to become cobalt 60, which decays to nickel 60, and the process goes on and on, producing successively heavier elements. It typically takes an atomic nucleus about a year to capture a neutron by this process so each unstable nucleus decays to the more stable form before the next neutron is added. The s-process is responsible for the synthesis of most heavy elements on Earth and in the solar system and universe, including the atoms in common things such as gold in jewelry, lead in batteries, and nearly all of the other heavy metals and elements.

Elements heavier than bismuth 209 can not be produced by the s-process since any nuclei heavier than bismuth 209 produced by neutron capture are unstable and immediately decay back to bismuth 209. Another mechanism, called the rapid or r-process is the only one known that can synthesize the heaviest elements such as thorium 232 and uranium 238, and this process occurs only in supernova explosions.

The violence of the first 15 minutes of a supernova explosion creates huge numbers of free neutrons so that the neutron capture rate of nuclei is so high that even unstable nuclei capture new neutrons before they can decay to more stable forms. The rapid bombardment of these nuclei with many neutrons in the first 15 minutes of the supernova creates all of the elements heavier than bismuth 209, explaining why these elements are so rare in the universe. This explains why the abundance of the heaviest elements (heavier than iron) is a billion times lower than the abundance of hydrogen and helium.

The early or primordial universe contained only hydrogen and helium, and all of the heavier elements were created in nucleosynthesis reactions inside stars or in supernova explosions. This model is supported by the observation that older globular clusters have more hydrogen and helium in them, and younger clusters are enriched in the heavier elements, having concentrated the remnants of novas and supernovas over time. Stars form when interstellar clouds are compressed by shock waves; then the stars evolve. Solar-sized stars evolve along the main sequence and end up as white dwarfs, and more massive stars end their lives in spectacular supernova explosions. Both processes spew heavy elements into interstellar space, where they may be captured in new interstellar clouds, and compressed into new stars by shock waves from supernova and other events.

See also ASTRONOMY; ASTROPHYSICS; CONSTELLATION; DWARFS (STARS); NOVA; ORIGIN AND EVOLUTION OF THE UNIVERSE.

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T

telescopes The word telescope comes from the Greek *tele* (far) and *skopein* (to look or see), meaning far-seeing. The Greek mathematician Giovanni Demisiani coined the word in 1611 for a refracting instrument designed by Galileo Galilei, who modified an instrument built a few years earlier in 1608 in the Netherlands by two spectacle makers, Hans Lippershey and Zacharias Janssen. In 1616 the Italian Jesuit astronomer and physicist Niccolo Zucchi invented the first reflecting telescope, which Isaac Newton improved in 1668. Now the term *telescope* is used to describe a wide range of scientific instruments that observe remote objects by collecting electromagnetic radiation from them and enhancing this radiation by different processes in different types of telescopes. In the 20th century a wide range of types of telescopes were designed and constructed to collect and enhance radiation from a wide variety of wavelengths in the spectrum.

Many different types of telescopes exist, with the most common being optical telescopes. Optical telescopes are widely used in astronomy, and similar technology is also used in many other practical instruments such as in spotting telescopes, binoculars and monoculars, camera lenses, and theodolites for surveying instruments. Optical telescopes collect and focus light from the visible part of the electromagnetic spectrum, whereas other types of telescopes work in the infrared and ultraviolet wavelengths. These telescopes increase the angular size and apparent brightness of distant objects by using a series of curved optical elements (lenses or mirrors) to gather the light and focus it at a focal point where it is enhanced from the original strength. The different types of optical telescopes include the following:

- refracting telescopes, which use lenses to enhance the light and form an image
- reflecting telescopes, which use mirrors to form the image
- catadioptric telescopes, which use a combination of lenses and mirrors to form the image

Radio telescopes collect electromagnetic radiation from distant objects using directional radio antennas with a parabolic shape, and these are often arranged in groups. They are designed using a conductive wire mesh with openings that are smaller than the wavelength being observed. When these large antennae are arranged in groups they can collect data with a wavelength that is similar in size to the separation between the antenna dishes. One such array of radio telescopes is the Very Large Array located in Socorro, New Mexico. The individual telescopes in this array can be moved so that they have different separations; in this way they can be used to collect data from a wide variety of wavelengths. This process is known as aperture synthesis. Distant radio telescopes can be linked in this process to study very long wavelengths, a process known as Very Long Baseline Interferometry (VLBI). The largest array size exceeds the diameter of the Earth. The VLBI Space Observation Program satellite uses a space-based system established by Japan in 2005. Radio telescopes can also be used to collect and study microwave radiation, such as signals from distant and faint quasars.

X-ray and gamma-ray telescopes collect radiation of these wavelengths that can pass through most metal and glass. Since the Earth's atmosphere is opaque to X-rays and gamma-rays, these telescopes must be based in space or from high-flying balloons. Most of these telescopes use a system of ring-shaped glancing mirrors that reflect the rays only a few degrees and do not completely focus the radiation. Instead the signal is interpreted using a system called coded aperture masks, where the patterns of shadows on the altered images can be interpreted to form an image.

See also astronomy; Brahe, Tycho; cosmic microwave background radiation; electromagnetic spectrum; Galilei, Galileo; Kepler, Johannes; quasar; radio galaxies; remote sensing.

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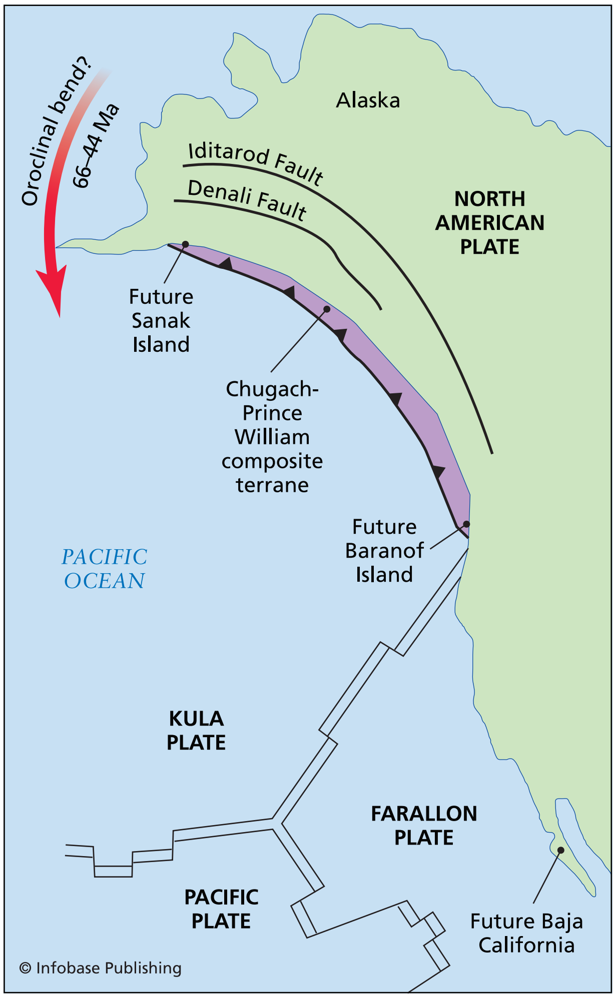
Tertiary

The Tertiary is first period of the Cenozoic era, extending from the end of the Cretaceous of the Mesozoic at 66 million years ago until the beginning of the Quaternary 1.6 million years ago. The Tertiary is divided into two periods, the older Paleogene (66–23.8 Ma) and the younger Neogene (23.8–1.8 Ma), and further divided into five epochs, the Paleocene (66–54.8 Ma), Eocene (54.8–33.7 Ma), Oligocene (38.7–23.8 Ma), Miocene (23.8–5.3 Ma), and Pliocene (5.3–1.6 Ma). The term *Tertiary* was first coined by the Italian geologist Giovanni Arduino in 1758 and later adopted by Charles Lyell in 1833 for his post-Mesozoic sequences in western Europe. The term *Tertiary* is being gradually replaced by the terms *Paleogene* and *Neogene* periods.

The Tertiary is informally known as the "age of mammals" for its remarkably diverse group of mammals, including marsupial and placental forms that appeared abruptly after the extinction of the dinosaurs. The mammals radiated rapidly in the Tertiary while climates and seawater became cooler. The continents moved close to their present positions by the end of the Tertiary, with major events including the uplift of the Himalayan-Alpine mountain chain.

Pangaea continued to break apart through the early Tertiary, while the African and Indian plates began colliding with Eurasia, forming the Alpine-Himalayan mountain chain. Parts of the Cordilleran mountain chain experienced considerable amounts of strike-slip translation of accreted terranes, with some models suggesting thousands of kilometers of displacement of individual terranes. The Cordillera of western North America experienced an unusual geologic event with the subduction of at least one oceanic spreading ridge beneath the convergent margin. The boundaries between three plates moved rapidly along the convergent margin from about 60 million years ago in the north to about 35 million years ago in the south, initiating a series of geological consequences including anomalous magmatism, metamorphism, and deformation. New subduction zones were initiated in the southwest Pacific (South-



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Schematic plate reconstruction of western North America and the NE Pacific Ocean for the Tertiary, showing the Kula-Farallon spreading center interacting with the convergent margin of North America and meeting the Kula-Pacific and Farallon-Pacific spreading centers far offshore in the paleo–Pacific Ocean east Asia) and in the Scotia arc in the south Atlantic. The Hawaiian-Emperor sea mount chain formed as a hot-spot track, with the oldest preserved record starting about 70 million years ago and a major change in the direction of motion of the Pacific plate recorded by a bend in the track near Midway Island formed 43 million years ago.

The San Andreas fault system was initiated about 30 million years ago as the East Pacific rise was subducted beneath western North America, and the relative motions between the Pacific plate and the North American plate became parallel to the margin. Around 3.5 million years ago the Panama arc grew, connecting North and South America, dramatically changing the circulation patterns of the world's oceans and influencing global climate. The East African rift system began opening about 5–2 million years ago, forming the sheltered environments that hosted the first known Homo sapiens.

Climate records show a general cooling of ocean waters and the atmosphere from the earliest Tertiary through the Paleocene, with warming then cooling in the Eocene. The oceans apparently became stratified with cold bottom waters and warmer surface waters in the Eocene, with further cooling reflecting southern glaciations in the Oligocene. Late Oligocene through Early Miocene records indicate a period of warming, followed by additional cooling in the mid-Miocene with the expansion of the Antarctic ice sheet that continued through the end of the Miocene. Pliocene climates began fluctuating wildly from warm to cold, perhaps as a precursor to the Pleistocene ice ages and interglacial periods. The Late Pliocene climates and change into the Pleistocene ice ages were strongly influenced by the growth of the Panama arc and the closing of the ocean circulation routes between the Pacific and Atlantic oceans. The Panama isthmus blocked warm Caribbean waters from moving west into the Pacific Ocean, but forced these waters into the Gulf Stream that brings warm water northward into the Arctic Ocean basin. Warm waters here cause increased evaporation and precipitation, leading to rapid growth of the northern glaciers.

Nearly all of the mammals present on the Earth today appeared in the Cenozoic, and most in the Tertiary, with the exception of a primitive group known as the pantotheres, which arose in the Middle Cretaceous. The pantotheres evolved into the first marsupial, the opossum, which in turn branched into the first placental mammals that spread over much of the northern continents, India, and Africa by the Late Cretaceous. Pantotheres and earlier mammals laid eggs, whereas marsupial offspring emerge from an eggshell-like structure in the uterus early in their development but then develop further in an external pouch. In contrast, placental mammals evolve more fully inside the uterus and emerge stronger with a higher likelihood of surviving infancy. It is believed that this evolutionary advantage led to the dominance of placental mammals and the extinction of the pantotheres.

Mammalian evolution in the Tertiary was strongly influenced by continental distributions. Some continents like Africa, Madagascar, India, and Australia were largely isolated. Connections or landbridges between some of these and other continents, such as the Bering landbridge between Alaska and Siberia, allowed communication of taxa between continents. With the land distribution patterns, certain families and orders evolved on one continent and others on other continents. Rhinoceroses, pigs, cattle, sheep, antelope, deer, cats, and related families evolved primarily in Asia, whereas horses, dogs, and camels evolved chiefly in North America, with some families reaching Europe. Horses have been used as a model of evolution with progressive changes in the size of the animals, as well as the complexity of their teeth and feet.

Marine faunas included gastropods, echinoids, and pelecypods along with bryozoans, mollusks, and sand dollars in shallow water. Coiled nautiloids floated in open waters, whereas sea mammals including whales, sea cows, seals, and sea lions inhabited coastal waters. The Eocene-Oligocene boundary is marked by minor extinctions, and the end of the Pliocene saw major marine extinctions caused by changes in oceanic circulation with massive amounts of cold waters pouring in from the Arctic and from meltwater from growing glaciers.

See also CENOZOIC; HISTORICAL GEOLOGY; NEOGENE; PLATE TECTONICS.

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thermodynamics Thermodynamics is the study of the transformation of heat into and from other forms of energy, particularly mechanical, chemical, and electrical energy. The science is concerned with energy conversions into heat and the relations of this conversion to variables including pressure, temperature, and volume. The name comes from the Greek *therme,* meaning heat, and *dynamis,* meaning power. Thermodynamics forms the basis of many principles of chemistry, physics, and earth sciences. The core of the science is based on statistical predictions of the collective motion of atoms and molecules based on their microscopic behavior. In this sense *heat* means energy in transit, and *dynamics* refers to movement, so thermodynamics can also be thought of as the study of the movement of energy. To study the movement of heat and energy between different objects, it is important to define systems and surroundings. For thermodynamics a system is defined as a group of particles whose average motion defines its properties, which are related to each other by equations of state (thermodynamic equations that describe the state of matter under a given set of physical conditions such as temperature, pressure, volume, or internal energy). Thermodynamics uses these equations to describe how systems respond to changes in their surroundings.

The study of thermodynamics rose from the study of steam engines and efforts to find ways to make them more efficient. The first law of thermodynamics states that energy can be neither created nor destroyed and that heat and mechanical work are mutually convertible. This is why moving engines get hot: The mechanical energy is transformed into heat energy. The second law of thermodynamics states that it is impossible for an unaided self-acting machine to transfer heat from a low-temperature body to a higher-temperature body. As an example, an ice cube can not make a cup of coffee warmer. Fundamental to the second law of thermodynamics is the quantity entropy (abbreviated as S), which is a measure of the unavailability of a system's energy to do work and is basically a measure of the randomness of the molecules in the system. The third law of thermodynamics states that it is impossible to reduce any system to absolute zero temperature (0°K, -273°C, or -459°F).

Energy is the capacity to do work, and it can exist in many different forms. Potential energy is energy of position, such as when an elevated body exhibits gravitational potential in that it can move to a lower elevation under the influence of gravity. Kinetic energy is the energy of motion and can be measured as the mean speed of the constituent molecules of a body. Einstein's theory of relativity showed that mass too can be converted to energy, as

$$E=mc^2$$

where E = energy, m = mass, and c = the speed of light. This remarkable relationship forms the basis of atomic power, and many mysteries of the universe.

Heat is a form of kinetic energy that manifests itself as motion of the constituent atoms of a substance. According to the laws of thermodynamics, heat may be transferred only from high-temperature bodies to lower-temperature bodies, and it does so by convection, conduction, or radiation. The specific heat of a substance is the ratio of the quantity of heat required to raise the temperature of a unit mass of the substance through a given range of temperature to the heat required to raise the temperature of an equal mass of water through the same range.

Conduction is the flow of heat through a material without the movement of any part of the material. The heat is transferred as kinetic energy of the vibrating molecules, which is passed from one molecule or atom to another. Convection is the transfer of heat through a fluid (liquid, gas, or slow-moving solid such as the Earth's mantle) by moving currents. Radiation is a heat transfer by infrared rays. All materials radiate heat, but hotter objects emit more heat energy than cold objects. Infrared radiation can pass through a vacuum and operates at the speed of light. Radiative heat can be reflected and refracted across boundaries, but it does not affect the medium through which it passes.

See also ATMOSPHERE; BLACK HOLES; CLOUDS; CONVECTION AND THE EARTH'S MANTLE; ENERGY IN THE EARTH SYSTEM; GEOCHEMISTRY; GEOPHYSICS; GRANITE, GRANITE BATHOLITH; HOT SPOT; MANTLE PLUMES; RADIOACTIVE DECAY; THUNDERSTORMS, TORNADOES.

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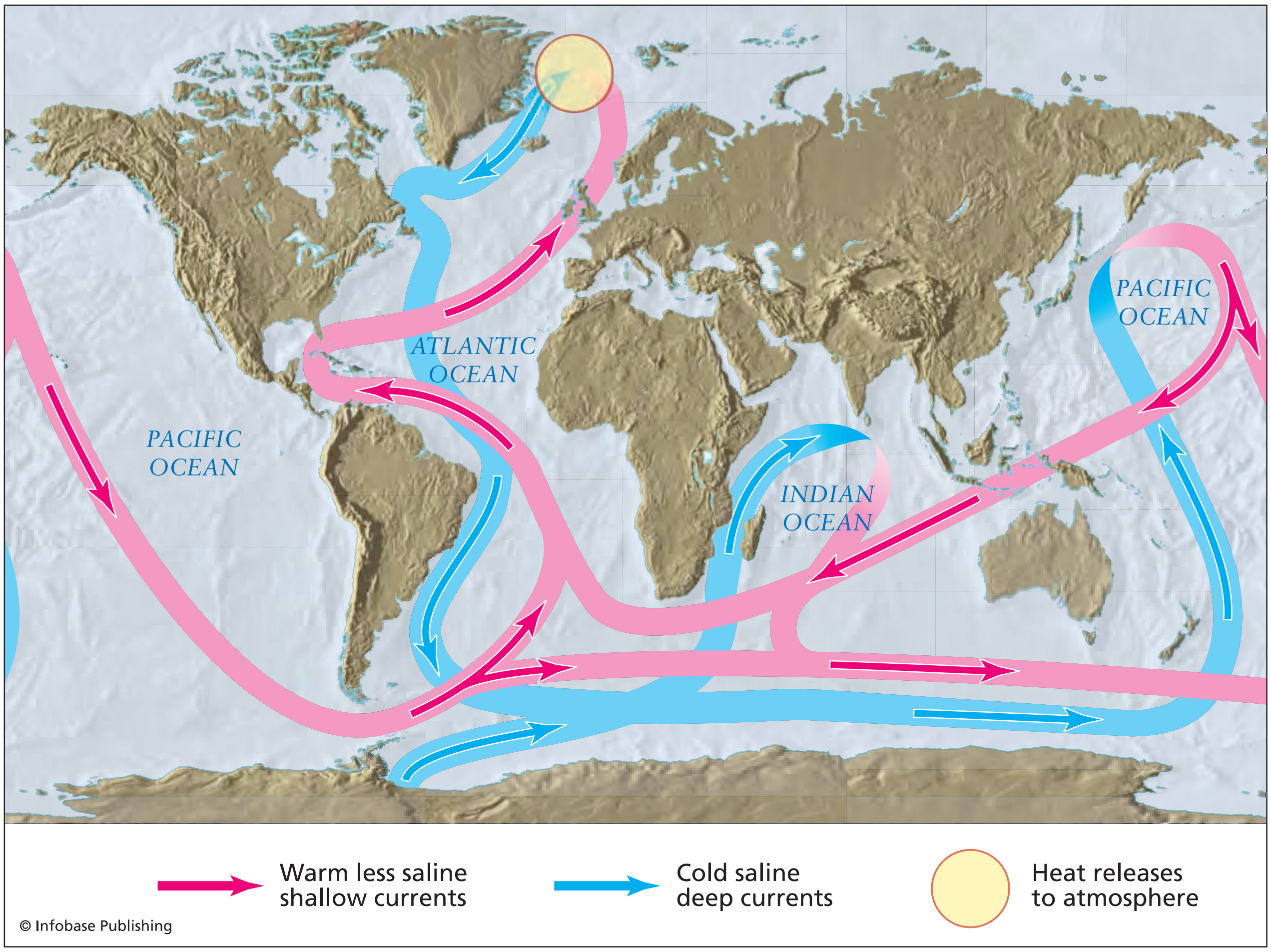
thermohaline circulation Thermohaline circulation refers to the vertical mixing of seawater driven by density differences caused by variations in temperature and salinity. Variations in formation and circulation of ocean water driven by thermohaline circulation may cause some of the thousands-of-years to decadal scale variations in climate. Cold water forms in the Arctic and Weddell Seas. This cold salty water is denser than other water in the ocean, so it sinks to the bottom and gets ponded behind seafloor topographic ridges, periodically spilling over into other parts of the oceans. The formation and redistribution of North Atlantic cold bottom water accounts for about 30 percent of the solar energy budget input to the Arctic Ocean every year. Eventually, this cold bottom water works its way to the Indian and Pacific Oceans where it upwells, gets heated, and returns to the North Atlantic. Variations in temperature and salinity that drive thermohaline circulation are found in waters that occupy different ocean basins and in those found at different levels in the water column. When the density of water at one level is greater than or equal to that below that level, the water column becomes unstable and the denser water sinks, displacing the deeper, less-dense waters below. When the dense water reaches the level at which it is stable it spreads out laterally and forms a thin sheet, forming intricately stratified ocean waters. Thermohaline circulation is the main mechanism responsible for the movement of water out of cold polar regions, and it exerts a strong influence on global climate. The upward movement of water in other regions balances the sinking of dense cold water, and these upwelling regions typically bring deep water, rich in nutrients, to the surface. Thus, regions of intense biological activity are often associated with upwelling regions.

The coldest water on the planet is formed in the polar regions, with large quantities of cold water originating off the coast of Greenland, and in the Weddell Sea of Antarctica. The planet's saltiest ocean water is found in the Atlantic Ocean, and this is moved northward by the Gulf Stream. As this water moves near Greenland it is cooled and then sinks to flow as a deep cold current along the bottom of the western North Atlantic. The cold water of the Weddell Sea is the densest on the planet, where surface waters are cooled to -35.4°F (-1.9°C), then sink to form a cold current that moves around Antarctica. Some of this deep cold water moves northward into all three major ocean basins, mixing with other waters and warming slightly. Most of these deep ocean currents move at a few to 10 centimeters per second.

Presently, the age of bottom water in the equatorial Pacific is 1,600 years, and in the Atlantic it is 350 years. Glacial stages in the North Atlantic have been correlated with the presence of older cold bottom waters, approximately twice the age of the water today. This suggests that the thermohaline



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Map of the world's oceans showing main warm and cold currents driven by thermohaline circulation

circulation system was only half as effective at recycling water during recent glacial stages, with less cold bottom water being produced during the glacial periods. These changes in production of cold bottom water may in turn be driven by changes in the North American ice sheet, perhaps itself driven by 23,000-year orbital (Milankovitch) cycles. Scientists suggest that a growth in the ice sheet would cause the polar front to shift southward, decreasing the inflow of cold saline surface water into the system required for efficient thermohaline circulation. Several periods of glaciation in the past 14,500 years (known as the Dryas) are thought to have been caused by sudden, even catastrophic injections of glacial meltwater into the North Atlantic, which would decrease the salinity and hence density of the surface water. This in turn would prohibit the surface water from sinking to the deep ocean, inducing another glacial interval.

Shorter-term decadal variations in climate in the past million years are indicated by so-called Heinrich events, defined as specific intervals in the sedimentary record showing ice-rafted debris in the North Atlantic. These periods of exceptionally large iceberg discharges reflect decadal-scale sea-surface and atmospheric cooling and are related to thickening of the North American ice sheet followed by ice stream surges associated with the discharge of the icebergs. These events flood the surface waters with low-salinity freshwater, leading to a decrease in flux to the cold bottom waters, and hence a short-period global cooling.

Changes in the thermohaline circulation rigor have also been related to other global climate changes. Droughts in the Sahel and elsewhere are correlated with periods of ineffective or reduced thermohaline circulation, because this reduces the amount of water drawn into the North Atlantic, in turn cooling surface waters and reducing the amount of evaporation. Reduced thermohaline circulation also reduces the amount of water that upwells in the equatorial regions, in turn decreasing the amount of moisture transferred to the atmosphere, reducing precipitation at high latitudes.

Atmospheric levels of greenhouse gases such as carbon dioxide (CO_2) and atmospheric temperatures show a correlation to variations in the thermohaline circulation patterns and production of cold bottom waters. CO_2 is dissolved in warm surface water and transported to cold surface water, which acts as a sink for the CO_2. During times of decreased flow from cold, high-latitude surface water to the deep ocean reservoir, CO_2 can build up in the cold polar waters, removing it from the atmosphere and decreasing global temperatures. In contrast, when the thermohaline circulation is vigorous, cold oxygen-rich surface waters downwell, and dissolve buried CO_2 and even carbonates, releasing this CO_2 to the atmosphere and increasing global temperatures.

The present-day ice sheet in Antarctica grew in the Middle Miocene, related to active thermohaline circulation that caused prolific upwelling of warm water that put more moisture in the atmosphere, falling as snow on the cold southern continent. The growth of the southern ice sheet increased the global atmospheric temperature gradients, which in turn increased the desertification of mid-latitude continental regions. The increased temperature gradient also induced stronger oceanic circulation, including upwelling and removal of CO_2 from the atmosphere, lowering global temperatures, and bringing on late Neogene glaciations.

Ocean bottom topography exerts a strong influence on dense bottom currents. Ridges deflect currents from one part of a basin to another and may restrict access to other regions, whereas trenches and deeps may focus flow from one region to another.

See also CLIMATE; CLIMATE CHANGE; OCEAN BASIN; OCEAN CURRENTS.

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thunderstorms, tornadoes Any storm that contains lightning and thunder may be called a thunderstorm. However, the term normally implies a gusty heavy rainfall event with numerous lightning strikes and thunder, emanating from a cumulonimbus cloud or cluster or line of cumulonimbus clouds. There is a large range in the severity of thunderstorms from minor to severe, with some causing extreme damage through high winds, lightning, tornadoes, and flooding rains.

Thunderstorms are convective systems that form in unstable rising warm and humid air currents. The air may start rising as part of a converging air system, along a frontal system, as a result of surface topography, or from unequal surface heating. The warmer the rising air is than the surrounding air, the greater the buoyancy forces acting on the rising air. Scattered thunderstorms that typically form in summer months are referred to as ordinary thunderstorms, and these typically are short-lived, produce only minor to moderate rainfall, and do not have severe winds. However, severe thunderstorms associated with fronts or combinations of unstable conditions may have heavy rain, hail, strong winds or tornadoes, and drenching or flooding rains.

Ordinary thunderstorms are most likely to form in regions where surface winds converge, causing parcels of air to rise, and where there is not significant wind shear or change in the wind speed and direction with height. These storms evolve through several stages, beginning with the cumulus or growth stage, where the warm air rises and condenses into cumulus clouds. As the water vapor condenses it releases a large amount of latent heat that keeps the cloud warmer than the air surrounding it and causes it to continue to rise and build as long as it is fed from air below. Simple cumulus clouds may quickly grow into towering cumulus congestus clouds in this way. As the cloud builds above the freezing level in the atmosphere, the particles in the cloud get larger and heavier and eventually are too large to be kept entrained in the air currents, and they fall as precipitation. As this precipitation is falling, drier air from around the storm is drawn into the cloud, but as the rain falls through this dry air it may evaporate, cooling the air. This cool air is then denser than the surrounding air and it may fall as a sudden downdraft, in some cases enhanced by air pulled downward by the falling rain.

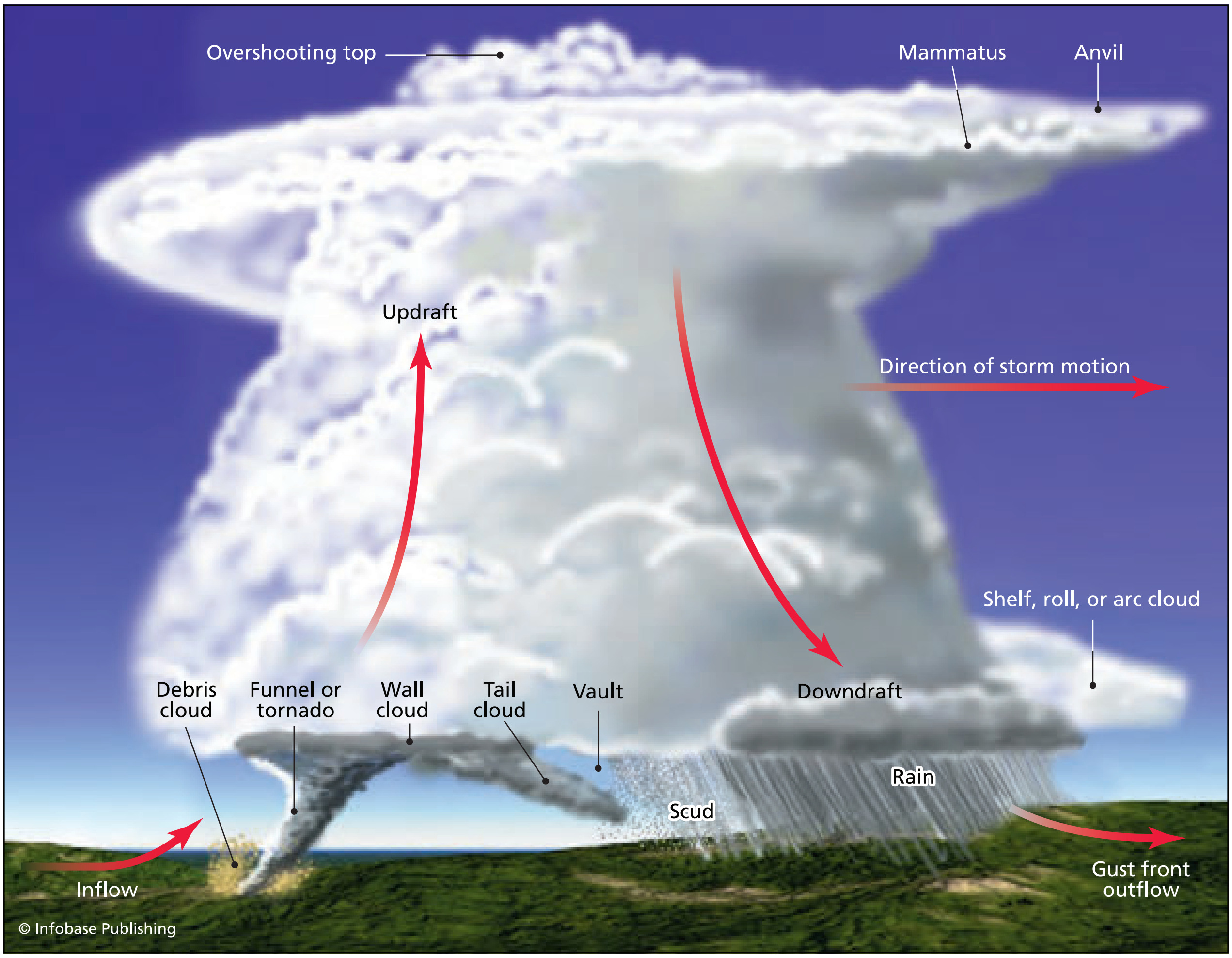
The development of downdrafts marks the passage of the thunderstorm into the mature stage, in which the upward and downward movement of air constitutes a convective cell. In this stage the top of the storm typically bulges outward in stable levels of the stratosphere, often around 40,000 feet (12,192 m), forming the anvil shape characteristic of mature thunderstorms. Heavy rain, hail, lightning, and strong, turbulent winds may come out of the base of the storms, which can be several miles in diameter. Cold downwelling air often expands out of the cloud base, forming a gust front along its leading edge, forcing warm air up into the storm. Most mature storm cells begin to dissipate after half an hour or so, as the gust front expands away from the storm and can no longer enhance the updrafts that feed the storm. These storms may quickly turn into gentle rains, and then evaporate, but the moisture may be quickly incorporated into new, actively forming thunderstorm cells.

Severe thunderstorms are more intense than ordinary storms, producing large hail, wind gusts of greater than 50 knots (57.5 m/hr, or 92.5 km/hr), more lightning, and heavy rain. Like ordinary thunderstorms, severe storms form in areas of upwelling unstable moist warm air, but severe storms tend to develop in regions where there is also strong wind shear. The high level winds have the effect of causing the rain that falls out of the storm to fall away from the region of upwelling air so that it does not have the effect of weakening the upwelling. In this way the cell becomes much longer lived and grows stronger and taller than ordinary thunderstorms, often reaching heights of 60,000 feet (18,288 m). Hail may be entrained for long times in the strong air currents and even thrown out of the cloud system at height, falling several kilometers from the base of the cloud. Downdrafts from severe storms are marked by bulbous mammatus clouds.

Supercell thunderstorms form where strong wind shear aloft is such that the cold downwelling air does not cut off the upwelling air, and a giant rotating storm with balanced updrafts and downdrafts may be maintained for hours. These storms may produce severe tornadoes, strong downbursts of wind, large (grapefruit-sized) hail, very heavy rains, and strong winds exceeding 90 knots (103.5 m/hr, or 167 km/hr).

Unusual winds are associated with some thunderstorms, especially severe storms. Gust fronts may be quite strong with winds exceeding 60 miles per hour (97 km/hr), followed by cold gusty and shifty winds. Gust fronts may be marked by lines of dust kicked up by the strong winds, or ominous-looking shelf clouds formed by warm moist air rising above the cold descending air of the gust front. In severe cases, gust fronts may force so much air upward that they generate new multi-celled thunderstorms with their own gust fronts that merge, forming an intense gust front called an outflow boundary. Intense downdrafts beneath some thunderstorms spread laterally outward at speeds sometimes exceeding 90 miles per hour (145 km/hr) when they hit the ground and are termed downbursts, microbursts, or macrobursts depending on their size. Some clusters of thunderstorms produce another type of unusual wind called a straight line wind, or derecho. These winds may exceed 90 miles per hour (145 km/hr), and extend for tens or even hundreds of miles.

Thunderstorms often form either in groups called mesoscale convective systems or as lines of storms called squall lines. Squall lines typically form along



Cross section of typical thunderstorm

or within a zone up to a couple of hundred miles in front of the cold front where warm air is compressed and forced upward. Squall lines may form lines of thunderstorms hundreds or even a thousand miles long, and many of the storms along the line may be severe with associated heavy rain, winds, hail, and tornadoes. Mesoscale convective complexes form when many individual thunderstorm cells across a region start to act together, forming an exceedingly large convective system that may cover more than 50,000 square miles (130,000 km^2). These systems move slowly and may be associated with many hours of flooding rains, hail, tornadoes, and wind.

Cumulonimbus clouds typically become electrically charged during the development of thunderstorms, although the processes that lead to the unequal charge distribution are not well known. About 20 percent of the lightning generated in thunderstorms strikes the ground, with most passing from cloud to cloud. Lightning is an electrical discharge that heats the surrounding air to 54,000°F (30,000°C), causing the air to expand explosively, creating the sound waves heard as thunder. As the air expands along different parts of the lightning stroke, the sound is generated from several different places, causing the thunder to have a rolling or echoing sound, enhanced by the sound waves bouncing off hills, buildings, and the ground. Cloud-to-ground lightning forms when negative electrical charges build up in the base of the cloud, causing positive charges to build in the ground. When the electrical potential gradient reaches 3 million volts per meter along several tens of meters, electrons rush to the cloud base and form a series of stepped leaders that reach toward the ground. At this stage, a strong current of positive charge moves up, typically along an elevated object, from the ground to the descending leader. As the two columns meet huge numbers of electrons rush to the ground, and a several-centimeter wide column of positively charged ions shoots up along the lightning stroke, all within one ten-thousandth of a second. The process then may be repeated several or even dozens of times along the same path, all within a fraction of a second.

TORNADOES

Tornadoes are a rapidly circulating column of air with a central zone of intense low pressure that reaches the ground. Most tornadoes extend from the bottom of severe thunderstorms or supercells as funnel-shaped clouds that kick up massive amounts of dust and debris as they rip across the surface. The exact shape of tornadoes is quite variable, from thin rope-like funnels, to classic cylindrical shapes, to powerful and massive columns that have almost the same diameter on the ground as at the base of the cloud. Many tornadoes evolve from an immature upward swirling mass of dust to progressively larger funnels that may shrink and tilt as their strength diminishes. Funnel clouds are essentially tornadoes that have not reached the ground. More tornadoes occur in the United States than anywhere else in the world, with most of these occurring in a region known as "tornado alley," extending from Texas through Oklahoma, Nebraska, Kansas, Iowa, Missouri, and Arkansas.

Most tornadoes rotate counterclockwise (as viewed from above) and have diameters from a few hundred feet (100 m) to a mile or more (2 km). Wind speeds in tornadoes range from about 40 miles per hour to more than 300 miles per hour (65–480 km/hr) and may move forward at a few miles per hour to more than 70 miles per hour (2–115 km/hr). Most tornadoes last for only a few minutes, but some last longer, with some reports of massive storms lasting for hours and leaving trails of destruction hundreds of miles long. Some supercell thunderstorms produce families or outbreaks of tornadoes, with half a dozen or more individual funnel clouds produced over the course of a couple of hours from a single storm.

The strength of winds and potential damage of tornadoes is measured by the Fujita scale, proposed by the tornado expert Dr. Theodore Fujita. The scale measures the rotational speed (not the forward speed) and classifies the tornadoes into F0–F5 categories.

Tornado crossing road near Manchester, South Dakota, June 24, 2003 *(Mike Berger/Photo Researchers, Inc.)*

Many tornadoes form in a region of the midwestern states known as tornado alley. This most commonly occurs in the springtime when cold air

FUJITA TORNADO SCALE

Scale	Category	Wind Speed	Damage Potential
F0	weak	40–72 mph	Minor; broken tree branches, damaged signs
F1	weak	73–112 mph	Moderate; broken windows, trees snapped
F2	strong	113–157 mph	Considerable; large trees uprooted, mobile homes tipped, weak structures destroyed
F3	strong	158–206 mph	Severe; trees leveled, walls torn from buildings, cars flipped
F4	violent	207–260 mph	Devastating; frame homes destroyed
F5	violent	261–318 mph	Incredible; strong structures damaged, cars thrown hundreds of yards

from the north overruns warm moist air from the Gulf of Mexico. Tornadic supercell thunderstorms form in front of the cold front as the warm moist air is forced upward in front of the cold air in this region. Supercell thunderstorms that have large rotating updrafts also spawn many tornadoes. Spinning roll clouds and vortexes may form as these storms roll across the plains, and if these horizontally spinning clouds are sucked into the storm by an updraft, the circulation may be rotated to form a tornadic condition that may evolve into a tornado. Before the supercell spawns a tornado, rotating clouds may be visible, and then a wall cloud may descend from the rotating vortex. Funnel clouds are often hidden behind the wall cloud, so these types of clouds should be eyed with caution.

Some tornadoes have formed from smaller and even nonsevere thunderstorms, from squall lines, and even smaller cumulus clouds. These types of tornadoes are usually short-lived, and less severe (F0–F1) than the supercell tornadoes. Waterspouts are related phenomena and include tornadoes that have migrated over bodies of water; they may also form in fair weather over warm shallow coastal waters. These weak (F0) funnel clouds form in updrafts, usually when cumulus clouds are beginning to form above the coastal region. Their formation is aided by converging surface air, such as when sea breezes and other systems meet.

See also ATMOSPHERE; CLOUDS; ENERGY IN THE EARTH SYSTEM; HURRICANES; METEOROLOGY; PRECIPITATION; THERMODYNAMICS.

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transform plate margin processes Processes that occur where two plates are sliding past each other along a transform plate boundary, either in the oceans or on the continents, are known as transform plate margin processes. Famous examples of transform plate boundaries on land include the San Andreas fault in California, the Dead Sea Transform in the Middle East, the East Anatolian transform in Turkey, and the Alpine fault in New Zealand. Transform boundaries in the oceans are numerous, including the many transform faults that separate segments of the mid-ocean ridge system. Some of the larger transform faults in the oceans include the Romanche in the Atlantic, the Cayman fault zone on the northern edge of the Caribbean plate, and the Eltanin, Galápagos, Pioneer, and Mendocino fault zones in the Pacific Ocean.

Three main types of transform faults are those that connect segments of divergent boundaries (ridge-ridge transforms), offsets in convergent boundaries, and those that transform the motion between convergent and divergent boundaries. Ridge-ridge transforms connect spreading centers and develop with this geometry because it minimizes the ridge segment lengths and therefore minimizes the dynamic resistance to spreading. Ideal transforms have purely strike-slip motions and maintain a constant distance from the pole of rotation for the plate.

Transform segments in subduction boundaries are largely inherited configurations formed in an earlier tectonic regime. In collisional boundaries the inability of either plate to be subducted yields a long-lived boundary instability, often formed to compensate the relative motion of minor plates in complex collisional zones, such as that between Africa and Eurasia.

The evolution of the San Andreas-Fairweather fault system best represents the development of a divergent-convergent boundary. When North America overrode the East Pacific rise, the relative velocity structure was such that a transform resulted, with a migrating triple junction that lengthened the transform boundary.

TRANSFORM BOUNDARIES IN THE CONTINENTS

Transform boundaries on the continents include the San Andreas fault in California, the North Anatolian fault in Turkey, the Alpine fault in New Zealand, and, by some definitions, the Altyn Tagh and Red River faults in Asia. Transform faults in continents show strike-slip offsets during earthquakes and are high angle faults with dips greater than 70°. They never occur as a single fault, but rather as a set of subparallel faults. The faults are typically subparallel because they form along theoretical slip lines (along small circles about the pole of rotation), but the structural grain of the rocks interferes with this prediction. The differences between theoretical and actual fault orientations leads to the formation of segments that have pure strike-slip motions and segments with compressional and extensional components of motion.

Extensional segments of transform boundaries form at left steps in left-slipping (left lateral) faults and at right steps in right-slipping (right lateral) faults. Movement along fault segments with exten-

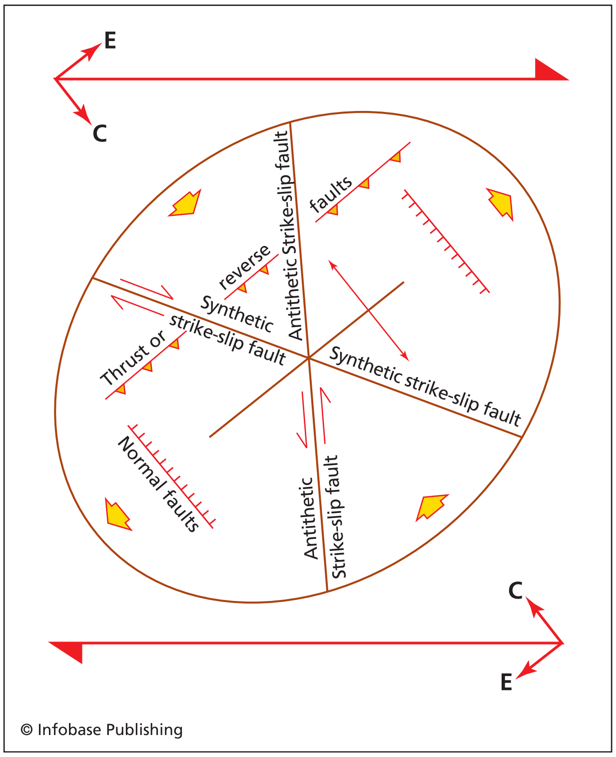
San Andreas Fault in Carrizo Plain, California, marking the transform plate boundary between North America and Pacific plates *(USGS)*

sional bends generates gaps where deep basins known as pull-apart basins form. The planet presently has about 60 active pull-apart basins, including locations like the Salton trough along the San Andreas Fault and the Dead Sea along the Dead Sea transform. Pull-apart basins tend to form with an initially sigmoid form, but as movement on the fault continues, the basin becomes very elongate parallel to the bounding faults. In some cases the basin may extend so much that oceanic crust is generated in the center of the pull-apart, such as along the Cayman trough in the Caribbean. Pull-apart basins have stratigraphic and sedimentologic characteristics similar to rifts, including rapid lateral facies variations, basin-marginal fanglomerate and conglomerate deposits, interior lake basins, and local bimodal volcanic rocks. They are typically deformed soon after they form, however, with folds and faults typical of strike-slip regime deformation.

Compressional bends form at right bends in left lateral faults, and left bends in right lateral faults. These areas are characterized by mountain ranges and thrust-faulted terrain that uplift and aid erosion of the extra volume of crust compressed into the bend in the fault. Examples of compressional (or restraining) bends include the Transverse Ranges along the San Andreas fault and Mount McKinley along the Denali fault in Alaska. Many of the faults that form along compressional bends have low-angle dips toward the main strike-slip fault but progressively steeper dips toward the center of the main fault. This forms a distinctive geometry known as a flower or palm tree structure, with a vertical strike-slip fault in the center and branches of mixed thrust/strike-slip faults branching off the main fault.

In a few places along compressional bends, two thrust-faulted mountain ranges may converge, forming a rapidly subsiding basin between the faults. These basins are known as ramp valleys. Many ramp valleys started as pull-apart basins, and became ramp valleys when the fault geometries changed.

A distinctive suite of structures that form in predictable orientations characterizes transform plate margins. Compressional bends form at high angles to the principal compressive stress and at about 30–45° from the main strike-slip zone. These are often associated with flower structures, containing a strike-slip fault at depth, and folds and thrusts near the surface. Dilational bends often initiate with their long axes perpendicular to the compressional bends, but large



Orientation of structures in transform margins, including strike-slip faults, normal faults, and thrust faults amounts of extension may lead to the long axis being parallel to the main fault zone. Folds, often arranged in en echelon or a stepped manner, typically form at about 45° from the main fault zone, with the fold axes developed perpendicular to the main compressive stress. The sense of obliquity of many of these structures can be used to infer the sense of shear along the main transform faults.

Strike-slip faults along transform margins often develop from a series of en echelon fractures that initially develop in the rock. As the strain builds up, the fractures are cut by new sets of fractures known as Riedel fractures, in new orientations. Eventually, after several sets of oblique fractures have cut the rock, the main strike-slip fault finds the weakest part of the newly fractured rock to propagate through, forming the main fault.

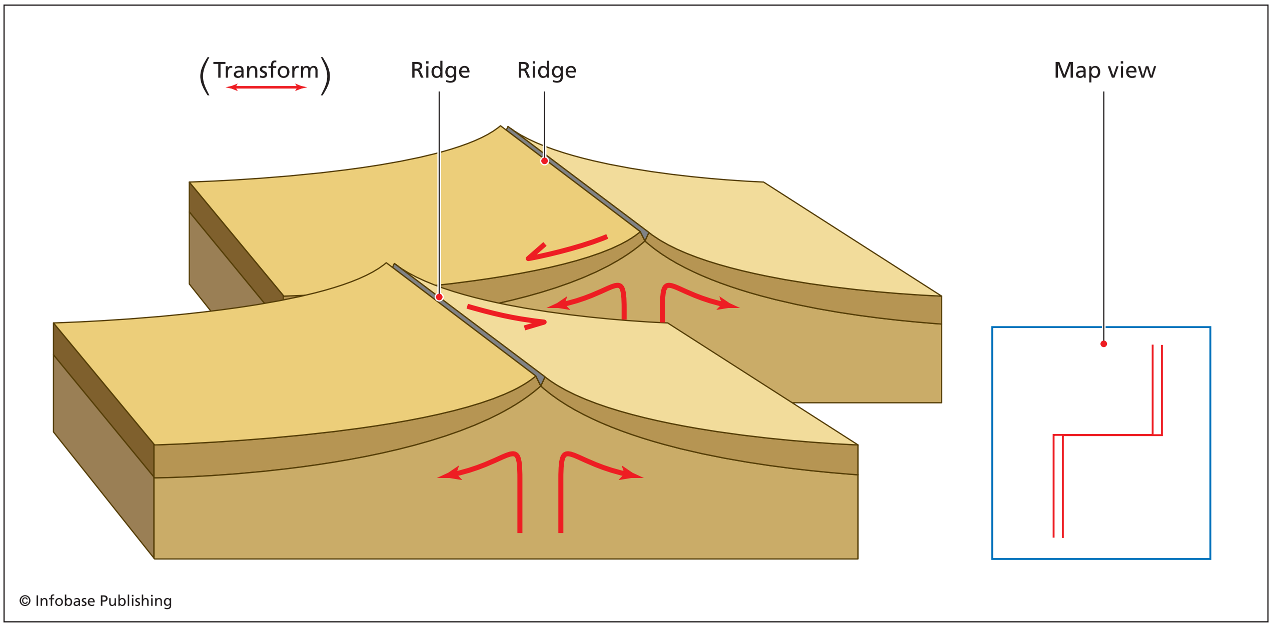
TRANSFORM BOUNDARIES IN THE OCEANS

Transform plate boundaries in the oceans include the system of ridge-ridge transform faults that are an integral part of the mid-ocean ridge system. Magma upwells along the ridge segments, cools and crystallizes, becoming part of one of the diverging plates. The two plates then slide past each other along the transform fault between the two ridge segments, until the plate on one side of the transform meets the ridge on the other side of the transform. At this point, the transform fault is typically intruded by mid-ocean ridge magma, and the apparent extension of the transform, known as a fracture zone, juxtaposes two segments of the same plate that move together horizontally. Fracture zones are not extensions of the transform faults, and they are no longer considered plate boundaries. After the ridge/transform intersection is passed, the fracture zone juxtaposes two segments of the same plate. There is typically some vertical motion along this segment of the fracture zone, since the two segments of the plate have different ages, and subside at different rates.

The transform and ridge segments preserve an orthogonal relationship in almost all cases, because this geometry creates a least work configuration, creating the shortest length of ridge possible on the spherical Earth.

Transform faults generate very complex geological relationships. They juxtapose rocks from very different crustal and even mantle horizons, show complex structures, exhibit intense alteration by high-temperature metamorphism, and have numerous igneous intrusions. Rock types along oceanic transforms typically include suites of serpentinite, gabbro, pillow lavas, lherzolites, harzburgites, amphibolite-tectonites, and even mafic granulites.

Transform faults record a very complex history of motion between the two oceanic plates. The relative motion includes dip-slip (vertical) motions due to subsidence related to the cooling of the oceanic crust. A component of dip-slip motion occurs all along the transform, except at one critical point, known as the



Three-dimensional view of a transform fault in the ocean basin, apparently offsetting a segment of the mid-ocean ridge. The sense of motion on the transform is opposite the apparent offset. Note that the lateral motion between the two segments of the oceanic crust ceases once the opposite ridge segment is passed. At this point, magmas from the ridge intrude the transform, and the contact becomes an igneous contact.

crossover point, where the transform juxtaposes oceanic lithosphere of the same age formed at the two different ridge segments. This dip-slip motion occurs along with the dominant strike-slip motion, recording the sliding of one plate past the other.

Fracture zones are also called nontransform extension regions. The motion along the fracture zone is purely dip-slip, due to the different ages of the crust with different subsidence rates on either side of the fracture zone. The amount of differential subsidence decreases with increasing distance from the ridge, and the amount of dip-slip motion decreases to near zero after about 60 million years. Subsidence decreases according to the square root of age.

Transform faults in the ocean may juxtapose crust with vastly different ages, thickness, temperature, and elevation. These contrasts often lead to the development of a deep topographic hole on the ridge axis at the intersection of the ridge and transform. The cooling effects of the older plate against the ridge of the opposing plate influences the axial rift topography all along the whole ridge segment, with the highest topographic point on the ridge being halfway between two transform segments. Near transform zones, magma will not reach its level of hydrostatic equilibrium because of the cooling effects of the older cold plate adjacent to it. Therefore, the types and amounts of magma erupted along the ridge are influenced by the location of the transforms.

Transform faults are neither typically vertical planes nor are they always straight lines connecting two ridge segments. The fault planes typically curve toward the younger plate with depth, since they tend to seek the shortest distance through the lithosphere to the region of melt. This is a least energy configuration, and it is easier to slide a plate along a vertically short transform than along an unnecessarily thick fault. This vertical curvature of the fault causes a slight change in the position and orientation of the fault on the surface, causing it to bend toward each ridge segment. These relationships cause the depth of earthquakes to decrease away from the crossover point, due to the different depth of transform fault penetration. Motion on these curved faults also influences the shape and depth of the transform-ridge intersection, enhancing the topographic depression and in many causing the ridge to curve slightly into the direction of the transform. Faults and igneous dikes also curve away from the strike of the ridge, toward the direction of the transform in the intersection regions.

Many of the features of ridge-transform intersections are observable in some ophiolite complexes (on-land fragments of ancient oceanic lithosphere), including the Arakapas transform in Troodos ophiolite in Cyprus and the Coastal complex in the Bay of Islands ophiolite in Newfoundland.

EXAMPLES OF EARTHQUAKE DISASTERS ALONG TRANSFORM PLATE BOUNDARIES

Transform plate margins sometimes also have large earthquakes, typically up to magnitude 8. These events can be quite devastating but are not as big as the magnitude 9+ events that may occasionally strike convergent margins. However, the distinction between a magnitude 9 and a magnitude 8 earthquake will not matter to people who are in collapsing buildings and cities devastated by these massive destructive events. Some plate boundaries have characteristics of both convergent margins and transform margins, such as where a plate is being subducted obliquely and part of the overriding plate moves sideways along the plate margin. These margins, such as southeastern Alaska or northern Sumatra–Andaman Islands, may have both subduction zone earthquakes (along the Benioff or subduction zone) and transform margin earthquakes (with the hypocenter located along the transform fault in the overriding plate). Some of the most famous of all earthquakes have occurred along transform plate boundaries. The following is a set of examples that describes some of the more significant earthquakes to strike transform margins in history.

San Francisco, 1906 (magnitude 7.8)

Perhaps the most infamous earthquake of all time is the magnitude 7.8 temblor that shook San Francisco at 5:12 A.M. on April 18, 1906, virtually destroying the city, crushing 315 people to death and killing 700 people throughout the region. Many of the unreinforced masonry buildings that were common in San Francisco immediately collapsed, but most steel and wooden frame structures remained upright. Ground shaking and destruction were most intense where structures were built on areas filled in with gravel and sand and least intense where the buildings were anchored in solid bedrock. Most of the destruction from the earthquake came not from ground shaking, but from the intense firestorm that followed. Gas lines and water lines were ruptured, and fires started near the waterfront that worked their way into the city. Other fires were inadvertently started by people cooking in residential neighborhoods and by people dynamiting buildings trying to avoid collapses and stop the spread of the huge fire. It has even been reported that some fires were started by individuals in attempts to collect insurance money on their slightly damaged homes. In all, 490 city blocks were burned.

The problems did not cease after the earthquake and fires but continued to worsen as a result of the poor sanitary and health conditions that followed as a consequence of the poor infrastructure. Hundreds of cases of bubonic plague claimed lives, and dysentery and other diseases combined to bring the death total to as high as 5,000.

One of the lessons that could have been learned from this earthquake was not appreciated until many years later—that is, that loose unconsolidated fill tends to shake more than solid bedrock during earthquakes. San Franciscans noted that some of the areas that shook the most and suffered from the most destruction were built on unconsolidated fill. After the 1906 earthquake, much of the rubble was bulldozed into San Francisco Bay, and later construction on this fill became the Marina district, which saw some of the worst damage during the 1989 Loma Prieta earthquake.

Loma Prieta, 1989 (magnitude 7.1)

The San Francisco area and smaller cities to the south, especially Santa Cruz, were hit by a moderate-sized earthquake (magnitude 7.1) at 5:04 P.M. on Tuesday, October 17, 1989, during live broadcast of the World Series baseball game. Sixty-seven people died, 3,757 people were injured, and 12,000 left homeless. Tens of millions of people watched on television as the earthquake struck just before the beginning of game three, and the news coverage that followed was unprecedented in the history of earthquakes.

The earthquake was caused by a rupture along a 26-mile- (42-km-) long segment of the San Andreas fault near Loma Prieta peak in the Santa Cruz Mountains south of San Francisco. The segment of the fault that had ruptured was the southern part of the same segment that ruptured in the 1906 earthquake, but this rupture occurred at greater depths and involved some vertical motion as well as horizontal motion. The actual rupturing lasted only 11 seconds, during which time the western (Pacific) plate slid almost six feet (1.9 m) to the northwest, and parts of the Santa Cruz Mountains were uplifted by up to four feet (1.3 m). The rupture propagated at 1.24 miles per second (2 km/sec) and was a relatively short-duration earthquake for one of this magnitude. Had it been much longer, the damage would have been much more extensive. As it was, the damage totals amounted to more than 6 billion dollars.

The actual fault plane did not rupture the surface, although many cracks appeared and slumps formed along steep slopes. The Loma Prieta earthquake had been predicted by seismologists, because the segment of the fault that slipped had a noticeable paucity of seismic events since the 1906 earthquake and was identified as a seismic gap with a high potential for slipping and causing a significant earthquake. The magnitude 7.1 event and the numerous aftershocks filled in this seismic gap, and the potential for large earthquakes along this segment of the San Andreas fault is now significantly lower. There are, however, other seismic gaps along the San Andreas fault in heavily populated areas that should be monitored closely.

Turkey, 1999 (magnitude 7.8)

On August 17, 1999, a devastating earthquake measuring 7.4 on the Richter scale hit heavily populated areas in northwestern Turkey at 3:02 A.M. local time. The epicenter of the earthquake was near the industrial city of Izmit about 60 miles (100 km) east of Istanbul, near the western segment of the notorious North Anatolian strike-slip fault. The earthquake formed a surface rupture more than 75 miles (120 km) long, along which offsets were measured between four and 15 feet (1.5–5 m). This was the deadliest and most destructive earthquake in the region in more than 60 years, causing more than 30,000 deaths and the largest property losses in Turkey's recorded history. The World Bank estimated that direct losses from the earthquake were approximately 6.5 billion dollars, with perhaps another 20 billion dollars in economic impact from secondary and related losses.

The losses from this moderate-sized earthquake were so high because

- The region in which it occurred is home to approximately 25 percent of Turkey's population.
- The region hosts much of the country's industrial activity.
- In a recent construction boom, building codes were ignored.
- Large numbers of high-rise apartment buildings were constructed with substandard materials including extra-coarse and sandy cement.
- too few reinforcement bars in concrete structures
- general lack of support structures

Haiti, 2010 (magnitude 7.0)

On Tuesday, January 10, 2010, at 4:53 P.M., Port-au-Prince, the capital city of Haiti, was hit by a magnitude 7.0 earthquake that essentially leveled the city, killing an estimated 200,000 people and severely affecting another 3 million. As of January 31, 2010, about 150,000 bodies had been recovered, but of necessity many were dumped in mass graves outside the capital, so exact estimates of the number of people killed may never be known. Cities and towns outside the capital, such as Jacmel, Léogone, and Miragoune, were also severely damaged, with many buildings collapsing. At the time of this writing, the death toll from these outlying areas was not known, and aid was only beginning to reach the places three weeks after the quake. The quake was the largest in the region in the past 200 years and was felt throughout Haiti and the Dominican Republic, southeastern Cuba, eastern Jamaica, parts of Puerto Rico, the Bahamas, and as far as Florida and

Venezuela. Nearly every building in Port-au-Prince was crushed or severely damaged, including the presidential palace and the grand Hotel Montana, where many hundreds of foreign tourists, UN workers, and World Bank employees perished, and the UN headquarters, where more were killed. As of January 30, 2010, there were 54 aftershocks with magnitudes greater than 4.5, many causing additional damage and spreading fear among the population. The U.S. Geological Survey estimates that aftershocks will continue for months to years but diminish in intensity and frequency over time.

The earthquake occurred along the transform plate boundary between North America and the Caribbean plates, where the Caribbean plate is moving about 0.8 inches (2 cm) per year toward the east with respect to North America. Motion between North America and the Caribbean plates is divided between two major east-west trending strike-slip fault systems. The Septentrional fault system cuts across northern Haiti, whereas the Enriquillo-Plantain Garden fault system cuts through southern Haiti and the Port-au-Prince area. The earthquake was located on the Enriquillo-Plantain Garden fault system, at a depth of 8.1 miles (13 km). The shallow depth of this earthquake, coupled with the very lax building standards in Haiti (the poorest country in the Western Hemisphere), explain why the damage and death toll were so exceptionally high from this earthquake compared to larger earthquakes such as the magnitude 7.9 Wenchuan China earthquake of May 12, 2008, that killed an estimated 87,652 people.

The infrastructure of the port, airport, and roads leading into Port-au-Prince was all severely damaged by the earthquake, so it was initially very difficult to get rescue workers, aid, and relief supplies to the city. Some of the first rescuers to reach Port-au-Prince were from the Israeli Defense Forces, who set up a field hospital and performed search-and-rescue operations; the U.S. military, who sent paratroopers to maintain law and order and perform rescue operations; and the Dutch who sent rescue personnel. Many other agencies were able to get rescue teams and aid to the people of the city a few days later when the airport was secured by the U.S. military, and remarkably, survivors were still being pulled from the rubble 15 days after the main shock. After about two weeks the United States was able to get a hospital ship anchored offshore, where many thousands of injured people were treated.

The city prison in Port-au-Prince collapsed during the earthquake, and about 1,000 dangerous criminals are believed to have escaped. In the week after the quake, some desperate survivors started looting collapsed shops for food, water, and valuables, and some of the escaped prisoners are believed to have been behind some of the looting and crime.

SUMMARY

Transform boundaries develop where one plate simply slides past the other along a transform fault, with the most famous example being the San Andreas fault along the western North America transform boundary. Historical accounts of many earthquakes along transform boundaries have shown that the amount of death and destruction is closely related to the population density and quality of buildings in an area. If a huge earthquake hits an unpopulated area, it is of little consequence. However, even moderate-sized earthquakes have killed tens and even hundreds of thousands of people in areas with homes made of unreinforced concrete, piles of stones, or loose earth. Southern California is the most vulnerable area in the United States for future large earthquakes along a transform boundary in a densely populated area, and residents in that area need to be diligent in application of strict building codes, in development of earthquake warning systems, and in preparation of sophisticated emergency response plans.

Southern California is most likely to suffer a major earthquake in the next 50 years, although it is currently impossible to tell exactly when this earthquake might strike. Government disaster planners in potentially affected regions are devising emergency response plans, and building codes have been improved to make the people and infrastructure in these areas less prone to injury and damage. Continued studies and monitoring can continue to improve the science of earthquake prediction, perhaps one day saving thousands of lives.

See also CONVERGENT PLATE MARGIN PROCESSES; DIVERGENT PLATE MARGIN PROCESSES; OPHIOLITES; PLATE TECTONICS; STRUCTURAL GEOLOGY.

FURTHER READING

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tsunami, generation mechanisms A tsunami is a long-wavelength seismic sea wave generated by the sudden displacement of the seafloor. The name is of Japanese origin, meaning *harbor wave.* Tsunamis are also commonly called tidal waves, although this is improper because they have nothing to do with tides. Every few years, these giant sea waves rise unexpectedly out of the ocean and sweep over coastal communities, killing hundreds or thousands of people and causing millions of dollars in damage. Major tsunamis hit coastal areas in 1946, 1960, 1964, 1992, 1993, and 1998 in coastal Pacific regions, and in 2004 the Indian Ocean was swept by a tsunami that killed 283,000 people. In 1998 a catastrophic 50-foot- (15.2-m-) high wave unexpectedly struck Papua New Guinea, killing more than 2,000 people and leaving more than 10,000 homeless.

Tsunamis may be generated by any event that suddenly displaces the seafloor, which in turn causes the seawater to move suddenly to compensate for the displacement. Most tsunamis are caused by earthquakes on the seafloor or are induced by volcanic eruptions that suddenly boil or displace large amounts of water. Giant submarine landslides have initiated other tsunami, and it is even possible that gases dissolved on the seafloor may suddenly be released, forming a huge bubble that erupts upward to the surface, generating a tsunami. The most catastrophic tsunami in the geological record may have been thousands of feet (hundreds of meters) tall, generated when asteroids or meteorites impacted with Earth in the oceans, displacing huge amounts of water in a geological instant.

PLATE TECTONICS AND TSUNAMI GENERATION

The movement of the tectonic plates causes earthquakes. Nearly all of the convergent plate boundaries on the planet are located in the oceans, because the bending of oceanic plates into subduction zones causes the surface of the crust to be pulled down to several miles (several km) depth. Most of the largest earthquakes occur along convergent plate boundaries when large amounts of crust move at one time. The sudden movement of the seafloor must move huge volumes of water, and this displacement of water is what causes many tsunamis.

Earthquake-Induced Tsunamis

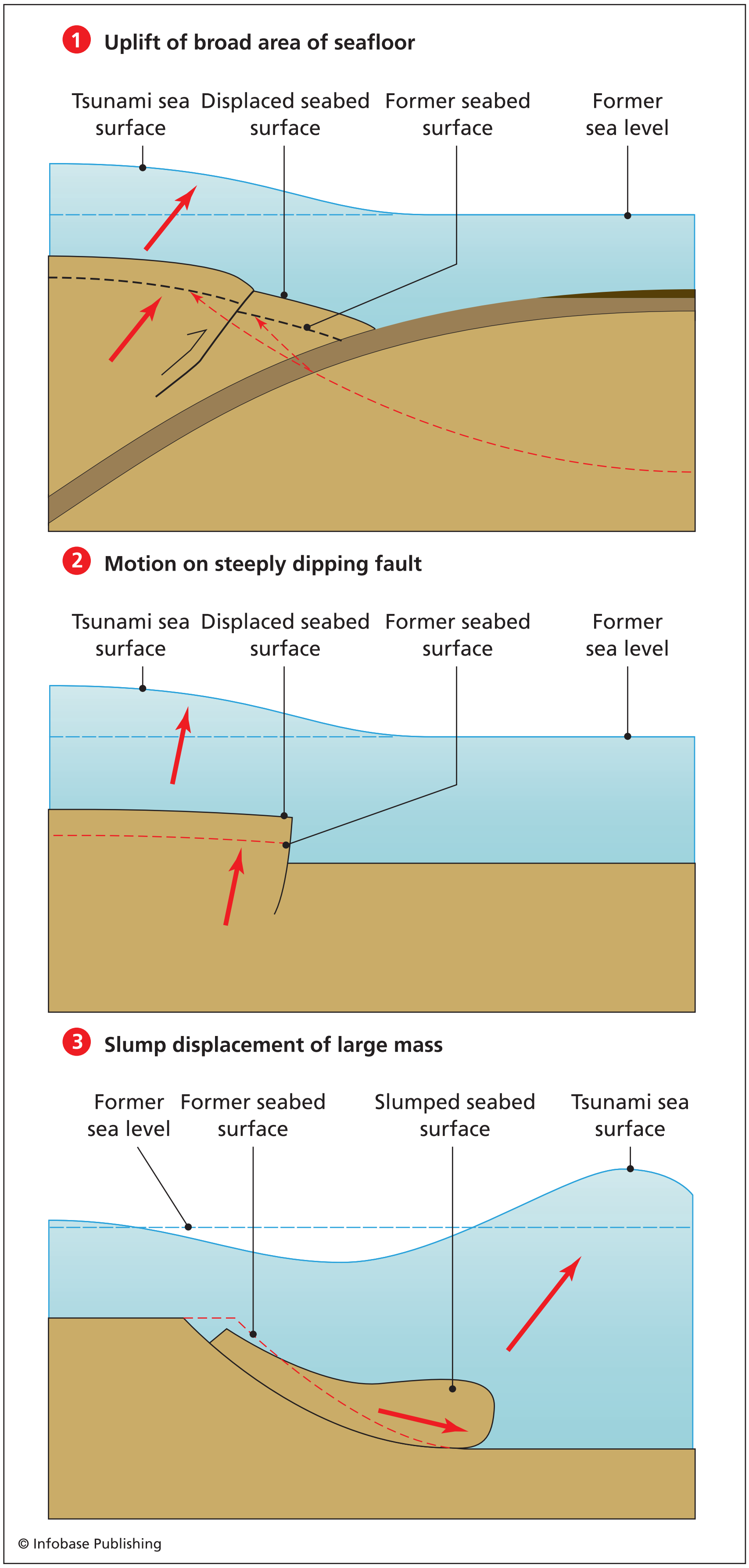
Earthquakes that strike offshore or near the coast have generated most of the world's tsunamis. In general, the larger the earthquake, the larger the potential tsunami, but this is not always the case. Some large earthquakes produce large tsunami, whereas others do not. Earthquakes that have large amounts of vertical displacement of the seafloor result in larger tsunamis than earthquakes that have predominantly horizontal movements of the seafloor. This difference is approximately a factor of 10, probably because earthquakes with vertical displacements are much more effective at pushing large volumes of water upward or downward, generating tsunamis. Another factor that influences the size of tsunami generated by an earthquake is the speed at which the seafloor breaks during the earthquake—slower ruptures tend to produce larger tsunamis. In general, earthquakes with a magnitude of 6.5 or greater, with a shallow focus or place of rupture, are required to generate a tsunami.

Tsunami earthquakes are a special category of earthquakes that generate tsunamis unusually large for the earthquake's magnitude. Tsunami earthquakes are generated by large displacements that occur along faults near the seafloor. Most are generated on steeply dipping seafloor surface penetrating faults that have vertical displacements along them during the earthquake, displacing the maximum amount of water. These types of earthquakes also frequently cause large submarine (underwater) landslides or slumps, which also generate tsunamis. In contrast to tsunamis generated by vertical slip on vertical faults, which cause a small region to experience a large uplift, other tsunamis are generated by movement on very shallowly dipping faults. These are capable of causing large regions to experience minor uplift, displacing large volumes of water and generating a tsunami. Some of the largest tsunamis may have been generated by earthquake-induced slumps along convergent tectonic plate boundaries. For example, in 1896 an earthquake-induced submarine slump generated a huge 75-foot (23-m) tsunami in Sanriku, Japan, killing 26,000 people in the wave. Another famous tsunami generated by a slump from an earthquake is the 1946 wave that hit Hilo, Hawaii. This tsunami was 50 feet (15 m) high, killed 150 people, and caused about $25 million in damage to Hilo and surrounding areas. The amazing thing about this tsunami is that it was generated by an earthquake-induced slump off Unimak Island in the Aleutian Chain of Alaska 4.5 hours earlier. This tsunami traveled at 500 miles per hour (800 km/hour) across the Pacific, hitting Hawaii without warning.

Another potent type of tsunami-generating earthquake occurs along subduction zones. Sometimes, when certain kinds of earthquakes strike in this environment, the entire forearc region above the subducting plate may snap upwards by up to a few tens of feet, displacing a huge amount of water. The devastating 2004 Indian Ocean tsunami was generated by motion of about a 600-mile- (1,000-km-) long segment of the forearc of the Sumatra arc and subduction zone. The tsunami generated during the 1964 magnitude 9.2 Alaskan earthquake also formed a tsunami of this sort, and it caused numerous deaths and extensive destruction in places as far away as California.

More rarely horizontal movements along vertical strike-slip faults may generate tsunamis. Sideways motion along strike-slip faults rarely generates tsunamis because the sideways motion on these faults

Diagram showing types of faults that generate large tsunamis, including (1) thrust faults in forearc regions, (2) vertical displacement of the seafloor, and (3) slumping of large blocks into the water



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does not cause the water surface to be directly disturbed.

Volcanic Eruption–induced Tsunamis

Some of the largest recorded tsunamis have been generated by volcanic eruptions. These may be associated with the collapse of volcanic slopes, debris and ash flows that displace large amounts of water, or submarine eruptions that explosively displace water above the volcano. Approximately 20 percent of volcanic-induced tsunamis form when volcanic ash or pyroclastic flows hit the ocean, displacing large amounts of water, and 20 percent form from earthquakes associated with the eruption. About 15 percent result from eruptions beneath the water, and 7 percent result from collapse of the volcano and landslides into the sea. The remaining causes are not known. The most famous volcanic eruption–induced tsunamis include the series of huge waves generated by the eruption of Krakatau in 1883, which reached run-up heights of 130 feet (36 m) and killed 36,500 people. The number of people that perished in the eruption of Santorini in 1600 B.C.E. is not known, but the toll must have been huge. The waves reached 800 feet (240 m) in height on islands close to the volcanic vent of Santorini. Flood deposits have been found 300 feet (90 m) above sea level in parts of the Mediterranean Sea and extend as far as 200 miles (320 km) southward up the Nile River. Several geologists suggest that these were formed from a tsunami generated by the eruption of Santorini. The floods from this eruption may also, according to some scientists, account for some historical legends such as the great biblical flood, the parting of the Red Sea during the exodus of the Israelites from Egypt, and the destruction of the Minoan civilization of the island of Crete.

The specific mechanisms by which volcanic eruptions can form tsunami are diverse but number fewer than a dozen. Perhaps the most common is from earthquakes associated with the volcanism. Many volcanic eruptions are accompanied by swarms of moderate-sized earthquakes, and some of these may be large enough to trigger tsunamis. This is especially true in cases of volcanoes built at convergent margins and that are partway under sea level, such as Mount Vesuvius in Italy. The 79 C.E. eruption of Vesuvius was associated with many earthquake-induced tsunamis, some being triggered before the main eruption, and others during and after the eruption.

When pyroclastic flows or nuées ardentes surge down the slopes of volcanoes they may eventually reach the ocean, where they displace water and spread laterally. Some pyroclastic flows are less dense than water and produce layers of ash and pumice that ride over the ocean surface, whereas others are denser than seawater and can suddenly displace large volumes of water, producing a tsunami. In these cases, the larger the flow, the larger the resulting tsunami. Some pyroclastic flows are dense, and continue to flow in a surgelike manner on the seafloor, pushing a wall of water ahead of the flow, thus generating a tsunami. The August 26, 1883, eruption of Krakatau in Indonesia generated an 33-foot- (10-m-) high tsunami by such an undersea surge of a pyroclastic flow, whereas the March 5, 1871, eruption of Ruang volcano, also in Indonesia, produced an 82-foot- (25-m-) high tsunami by this mechanism.

Submarine eruptions in shallow water can generate tsunamis by displacing water when the volcano erupts. When the water is deeper than about 1,650 feet (500 m), the weight of the water is so great that it suppresses the formation of surface waves. This is fortunate, since there are many volcanic eruptions along the 8,900-foot- (2,700-m-) deep mid-ocean ridges, and if each of these generated a tsunami, the coastal zone on most continents would be constantly plagued with tsunamis. When submarine eruptions expose the magma chamber of a volcano to seawater, larger tsunamis result from the sudden steam explosion as the cold seawater vaporizes immediately after touching the extremely hot magma. An explosion of this sort generated the deadly 1883 tsunami from the eruption of Krakatau in Indonesia, when a steam explosion formed a 130-foot (40-m) high tsunami that killed tens of thousands of people.

One of the most catastrophic ways to bring large volumes of seawater into sudden contact with a magma chamber is through the formation of a caldera, where the top of the volcanic complex suddenly collapses into the magma chamber, forming a large depression on the surface. If the volcano is located at or near sea level, ocean waters can suddenly rush into the depression, where they will encounter the hot magma and form giant steam eruptions. Many volcanoes around the Pacific Rim have formed caldera structures, and many appear to have generated tsunamis. The most famous is the tsunami associated with the formation of the caldera on Krakatau in 1883, in which the tsunami devastated the Sunda straits, killing thousands of people. Another example of a tsunami generated by the seawater rushing into a collapsing caldera is from Mount Ritter, in Papua New Guinea. On March 13, 1888, a 1.5-mile- (2.5-km-) wide caldera collapsed beneath the volcano, and the sea rushed in, generating a 50-foot- (15-m-) high tsunami that swept local shores. The actual amount of seawater displaced in tsunamis formed by caldera collapse is small, typically many orders of magnitude smaller than the amount displaced during large earthquakes. Therefore tsunamis associated with caldera collapse tend not to travel very far, but to decay in height quickly, according to the inverse of the square root of the distance from the source.

Tsunamis can be generated from volcanoes during collapse of the slopes and formation of landslides and debris avalanches that move into the ocean. Most tsunamis generated by the collapse of slopes of volcanoes are small, localized, and very directional, in that they propagate directly away from the landslide or debris avalanche and fade rapidly in other directions. Many volcanoes around the Pacific Rim have steep slopes near the sea and pose hazards for tsunamis generated by slope collapse. Some of these can be locally quite powerful, as shown by the example of Mount Unzen in Japan. On May 21, 1792, a large debris avalanche that roared off the slope of the volcano traveled four miles (6.5 km) and hit the seawater of the Ariake Sea. This displaced enough water to generate a tsunami with run-up heights of up to 170 feet (55 m) along a 50-mile- (77-km-) long section of coast on the Shimabara Peninsula, killing 14,524 people, destroying 6,000 homes, and sinking 1,650 ships. Other volcanic islands, such as Hawaii and the Canary Islands, pose a different kind of landslide threat, in which large sections of the volcano collapse, forming giant undersea landslides with associated tsunamis.

A final way that volcanoes can form tsunamis is through lateral blasts or sideways eruptions from the volcano. The most famous lateral blast from a volcano is the well-documented 1980 eruption of Mount St. Helens, but this was far from the ocean and did not generate a tsunami. Some volcanoes have a tendency to erupt sideways, one of these being Taal volcano in the Philippines, in which at least five lateral blasts have occurred in the past 250 years, each generating a deadly tsunami.

Mass-wasting processes on volcanic slopes have generated a number of other tsunamis, but these can generally be classified as being caused by landslides, or as one of the mechanisms from movement of lava discussed in this section. Mudflows and lahars have generated many local tsunamis; lava flows, if large and fast enough, can also generate local tsunamis. Most of these minor mechanisms generate only small, localized, and strongly directional tsunamis.

Landslide-induced Tsunamis

Landslides that displace large amounts of water generate many tsunamis. These may be from rock falls and other debris that falls off cliffs into the water, such as the huge avalanche that triggered a 200-foot- (60-m-) high tsunami in Lituya Bay, Alaska. Submarine landslides tend to be larger than avalanches that originate above the water line, and they have generated some of the largest tsunamis on records. Many submarine landslides are earthquake-induced, whereas others are triggered by storm events and by increases in pressure on the sediments on the continental shelf induced by rises in sea level. A deeper water column above the sediments on shelf or slope environment can significantly increase the pressure in the pores of these sediments, causing them to become unstable and slide downslope. After the last glacial retreat 6,000–10,000 years ago, sea levels have risen by 320–425 feet (100–130 m), which has greatly increased the pore pressure on continental slope sediments around the world. This increase in pressure is thought to have initiated many submarine landslides, including the large Storegga slides from 7,950 years ago off the coast of Norway.

Tsunamis are suspected of being landslide-induced when the earthquake is not large enough to produce the observed size of the associated tsunami. Many areas beneath the sea are characterized by steep slopes, including areas along most continental margins, around islands, and along convergent plate boundaries. Sediments near deep-sea trenches are often saturated in water and close to point of failure, where the slope gives out and collapses, causing the pile of sediments to slide suddenly down to deeper water depths. When an earthquake strikes these areas, large parts of the submarine slopes may give out simultaneously, displacing water and generating a tsunami. The 1964 magnitude 9.2 earthquake in Alaska generated more than 20 tsunamis, and these were responsible for most of the damage and deaths from this earthquake.

Some steep submarine slopes that are not characterized by earthquakes may also be capable of generating huge tsunamis. Recent studies along the east coast of North America, off the coast of Atlantic City, New Jersey, have revealed significant tsunami hazards. The submarine geology off the coast of eastern North America consists of a pile of unconsolidated sediments several thousands of feet (hundreds of meters) thick on the continental slope. These sediments are so porous and saturated with water that the entire slope is on the verge of collapsing under its own weight. A storm or minor earthquake may be enough to trigger a giant submarine landslide in this area, possibly generating a tsunami that could sweep across the beaches of Long Island, New Jersey, Delaware, and much of the east coast of the United States.

Storms are capable of generating submarine landslides even if the storm waves do not reach and disrupt the seafloor. Large storms are associated with storm surges that form a mound of water in front of the storm that may sometimes reach 20–32 feet (6–10 m) in height. As the storm surge moves onto the continental shelf it is often preceded by a drop in sea level caused by a drop in air pressure, so the storm surge may be associated with large pressure changes on the seafloor and in the pores of unconsolidated sediments. A famous example of a storm surge–induced tsunami is the catastrophic event that occurred in Tokyo, Japan, on September 1, 1923. On this day, a powerful typhoon swept across Tokyo and was followed that evening by a huge submarine landslide and earthquake that generated a 36-foot- (11-m-) tall tsunami that killed 143,000 people. Surveys of the seabed after the tsunami revealed that large sections had slid further into the sea, deepening the bay in many places by 300–650 feet (100–200 m), and locally by as much as 1,300 feet (400 m). Similar storm-induced submarine slides are known from many continental slopes and delta environments, including the Mississippi delta in the Gulf of Mexico and the coast of Central America.

Submarine slides are part of a larger group of processes that can move material downslope on the seafloor and that includes other related processes such as slumps, debris flows, grain flows, and turbidity currents. Submarine slumps are a type of sliding slope failure in which a downward and outward rotational movement of the slope occurs along a concave up-slip surface or fault. This produces either a singular or a series of rotated blocks, each with the original seafloor surface tilted in the same direction. Slumps can rapidly move large amounts of material short distances and are capable of generating tsunamis. Debris flows involve the downslope movement of unconsolidated sediment and water, most of which is coarser than sand. Some debris flows begin as slumps but then continue to flow downslope as debris flows. They typically fan out and come to rest when they emerge out of submarine canyons onto flat abyssal plains on the deep seafloor. Rates of movement in debris flows vary from several feet per year to several hundred miles per hour. Debris flows are commonly shaped like a tongue with numerous ridges and depressions. Large debris flows can suddenly move large volumes of sediment, so are also capable of generating tsunamis. Turbidity currents are sudden movements of water-saturated sediments that move downhill under the force of gravity. Typically, a water-saturated sediment on a shelf or shallow water setting is disturbed by a storm, earthquake, or some other mechanism that triggers the sliding of the sediment downslope. The sediment-laden water mixture then moves rapidly downslope as a density current and may travel tens or even hundreds of miles at tens of miles (km) per hour until the slope decreases, and the velocity of current decreases. As the velocity of the current decreases, the ability of the current to hold coarse material in suspension decreases. The current drops first its coarsest load, then progressively finer material as the current decreases further. Turbidity currents do not usually generate tsunamis, but many are associated with slumps and debris flows that may generate tsunamis. However, some turbidity flows are so massive that they may form tsunamis.

Volcanic hot-spot islands in the middle of some oceans have a long record of producing tsunamis from submarine landslides. These islands include Hawaii in the Pacific Ocean, the Cape Verde Islands in the North Atlantic, and Réunion in the Indian Ocean. The shape of many of these islands bears the telltale starfish shape with cuspate scars indicating the locations of old curved landslide surfaces. On average, a significant tsunami is generated somewhere in the world every 100 years by a collapse and submarine landslide from a mid-ocean volcanic island. These islands are volcanically active. Lava flows move across the surface and then cool and crystallize quickly as the lava enters the water. This causes the islands to grow upward as very steep-sided columns, whose sides are prone to massive collapse and submarine sliding. Many volcanic islands are built up with a series of volcanic growth periods followed by massive submarine landslides, effectively widening the island as it grows. However, island growth by deposition of a series of volcanic flows over older landslide scars causes the island to be unstable—the old landslide scars are prone to slip later since they are weak surfaces, and the added stress of the new material piled on top of them makes them unstable. Other processes may also contribute to making these surfaces and the parts of the island above them unstable. For instance, on the Hawaiian Islands, volcanic dikes have intruded along some old landslide scars, which can reduce the strength across the old surfaces by large amounts. Some parts of Hawaii are moving away from the main parts of the island by up to 0.5–4 inches (1–10 cm) per year by the intrusion of volcanic dikes along old slip surfaces. Also, many landslide surfaces are characterized by accumulations of weathered material and blocks of rubble that, under the additional weight of new volcanic flows, can help to reduce the friction on the old slip surfaces, aiding the generation of new landslides. Therefore, as the islands grow, they are prone to additional large submarine slides that may generate tsunamis.

The Cape Verde Islands, located in the eastern Atlantic off the coast of west Africa, were constructed from hot-spot style volcanism (i.e., not associated with the mid-ocean ridge or island arcs). The islands have very steep western slopes, and these cliffs are unstable. If new magma enters the volcanic islands, it may heat the groundwater in the fractures in the rock, creating enough pressure to induce the giant cliffs to collapse. Any landslides generated from such an anticipated collapse would have the potential to generate giant tsunamis, several thousand feet (several hundred meters) high, that could sweep the shores of the Atlantic. The wave height will diminish with distance from the Cape Verde Islands, but the effects on the shores of eastern North America, the Caribbean, and eastern South America are expected to be devastating, if this event ever occurs. The waves will probably also wrap around the Cape Verde Islands, hitting the United Kingdom and the west coast of Africa with smaller, but still damaging waves.

The characteristics of tsunamis generated by landslides depend on the amount of material that moves downslope, the depth that the material moves from and to, and the speed at which the slide moves. Tsunamis generated by submarine landslides are usually quite different from those generated by other processes such as displacements of the seafloor caused by earthquakes. Submarine slides move material in one direction, and the resulting tsunami tends also to be more focused in slide-induced events than from other triggering mechanisms. Therefore, tsunamis produced by submarine slides are characterized by a wave located above the slide that moves offshore parallel to the direction the slide has moved. A complementary wave is produced that moves in the opposite direction, upslope and toward shore.

Tsunamis resulting from submarine slides also have wave shapes that are different from waves generated by earthquake-induced displacement of the seafloor. Slide-induced tsunamis typically have a first wave with a small crest, followed by a deep trough that may be three times deeper than the height of the first wave. The next wave will have the height of the trough, but may change into several waves with time. The large height difference between the first wave and the succeeding trough often leads tsunamis generated by landslides to have greater run-up heights than tsunamis generated by other mechanisms. Slide-induced tsunamis also differ from other tsunamis in that they start with slow velocities as the submarine slide forms, then must accelerate as they take form. Therefore, the arrival time of a slide-induced tsunami at shore locations is typically later than expected. The wavelength of tsunamis from submarine slides is typically 0.5–6 miles (1–10 km), and the periods range from one to five minutes. The period may increase as the area of the slide increases and the slope of the seafloor decreases. Submarine landslides rarely move faster than 160 feet per second (50 m/sec), whereas the resulting tsunamis quickly accelerate to 325–650 feet per second (100–200 m/sec). The characteristics of slide-induced tsunamis are therefore quite different from tsunamis produced by other mechanisms.

Natural Gas and Gas Hydrate Eruption–induced Tsunamis

The continental shelves and slopes around most continents are the sites of deposition of very thick piles of sediments. River deltas such as the Mississippi delta may add even more sediments to these environments, in some cases forming piles of sediment that are 10 miles (16 km) thick, deposited over many millions of years. Natural gas is produced in submarine sediments by the anaerobic decay of organic matter that becomes buried with the sediments. The gas produced by the decay of these organic particles may escape or become trapped within the sediments. When the gas gets trapped between the pore spaces of the sediments, it causes the pressure to build up within the seafloor sediments; this process is called underconsolidation. These pressures may become quite large and even be greater than the pressure exerted by weight of the overlying water. The pressure from the weight of the water is called hydrostatic pressure. When the gas pressure within a layer or larger section of sediments on the continental shelves and slopes becomes greater than the hydrostatic pressure, the sediments on the slope are on the verge of failure, such that any small disturbance could cause a massive submarine landslide, in turn inducing a tsunami.

Decaying organic matter on the seafloor releases large volumes of gas, such as methane. Under some circumstances, including in cold water at deep depths, these gases may coagulate, forming gels called gas hydrates. It has recently been recognized that these gas hydrates occasionally spontaneously release their trapped gases in giant bubbles that rapidly erupt to the surface. Such catastrophic degassing of gas hydrates poses a significant tsunami threat to regions not previously thought to have a significant threat from this type of tsunami, such as along the eastern and gulf coasts of the United States.

Other Tsunamis

The largest tsunamis in the geological record are generated by the impact of giant asteroids with the earth. These types of events do not happen very often and none are known from historical records, but when they do occur they are cataclysmic. Geologists are beginning to recognize deposits of impact-generated tsunamis and now estimate that they may reach several thousand feet (1 km) in height. One such tsunami was generated about 66 million years ago by an impact that struck the shoreline of the Yucatán Peninsula, producing the Chicxulub impact structure. This impact produced a huge crater and sent a 3,000-foot- (1-km-) high tsunami around the Atlantic, devastating the Caribbean and the U.S. gulf coast. Subsequent fires and atmospheric dust that blocked the Sun for several years killed off many of the planet's species, including the dinosaurs. Even relatively small meteorites that hit the ocean have the potential to generate significant tsunamis. A meteorite only 1,000 feet (300 m) in diameter would produce a tsunami seven feet (2 m) tall that could strongly affect coastal regions for 600 miles (1,000 km) around the impact site. Statistical analysis predicts about a 1 percent chance of impact-related tsunami events happening once every 50 years.

Weather-related phenomena may also rarely generate tsunamis. In some special situations, large variations in atmospheric pressure, especially at temperate latitudes, can generate long-wavelength waves (tsunamis) that resonate, or become larger, in bays and estuaries. Although these types of tsunamis are not generated by displacement of the seafloor, they do have all the waveform characteristics of other tsunamis and are therefore classified as such.

PHYSICS OF TSUNAMI MOVEMENT

Witnessing the approach of a large tsunami to shore can be one of the most awe-inspiring and deadly sights ever witnessed by many residents of low-lying coastal areas. Tsunamis are very different from normal storm- or wind-generated waves, in that they have exceptionally long wavelengths, the distance between successive crests. Whereas most storm waves will rise, break, and dissipate most of their energy in the surf zone, tsunamis are characterized by rapid rise of sea level that leads the wave to break at the shoreline, then to keep on rising or running up into the coastal zone for extended periods of time. This is related to the long wavelength of tsunamis. Most waves have distances between the crests of several hundreds of feet (tens of m) and rise and fall relatively quickly as each wave crest passes. Tsunamis, however, may have distances between each wave crest of a hundred or even many hundreds of miles (km), so it may take half an hour, an hour, or more for the wave to stop its incessant and destructive rise into coastal areas and retreat into the sea, before the next crest of the tsunami train crashes into shore. Tsunamis are like normal wind-generated waves in that they have a series of wave crests separated by troughs. Therefore, like normal waves, after the first, typically hour-long wave sweeps through a coastal region and retreats, the tsunami event is not over. A series of wave crests follows, sometimes with the second or third crest being the largest, sweeping into the coastal areas, each crest causing its own destruction. Many of the deaths reported from tsunami disasters are associated with the fact that many people do not understand this basic physical principal about tsunamis, and they rush to the coastal area after the first destructive wave to rescue injured people and become victims of the second or third crest's incursion onto the land.

Movement in Open Ocean

Tsunamis are waves with exceptionally large distances between individual crests, and they move like other waves across the ocean. Waves are described using the terms related to the regular geometrically repeating pattern of the waves. Waves in a series are called a wave train, with regularly repeating crests and troughs. Wavelength is the distance between crests, wave-height is the vertical distance from the crest to the bottom of the trough, and the amplitude is one-half of the wave height. The period of the wave is the time between the passage of two successive crests. Most tsunamis have wave periods of 1.6 to 33 minutes. Most ocean waves have wavelengths of 300 feet (100 m) or less. Tsunamis are exceptional in that they have wavelengths that can exceed 120 miles (200 km). The particle motion in deepwater waves follows roughly circular paths, where particles move approximately in a circle, and return back to their starting position after the wave passes. The amount of circular motion decreases gradually with depth, until a depth that equals one-half of the wavelength. At this depth all motion associated with the passage of the wave stops, and the water beneath this point experiences no effect from the passage of the wave above. This depth is known as the wave base. The movement of deepwater waves is therefore associated with the transfer of energy, but not the transfer of water from place to place.

The particle motion of individual molecules of water during the passage of tsunamis is elliptical, similar to the circular motion of other deepwater waves. The motion of any particles during the passage of the waves follows elliptical paths, first forward, down, then up and back to near the starting point during the passage of individual wave crests. The passage of deep-water tsunamis is therefore associated with the movement and transportation of individual particles. The reason that particle paths in tsunamis are elliptical, and in other deepwater waves the motion is circular, is that tsunamis have such long wavelengths that the ocean's depth of 2–3 miles (3–5 km) is less than the wave base. Tsunamis therefore travel as shallow-water waves across the open ocean where the water depth is less than wave base, and they feel some frictional effects from the ocean bottom. This friction distorts the preferred circular particle paths into elliptical paths that are observed in tsunamis. The end result is that tsunamis are associated with motion of the entire water column during passage, whereas wind-generated waves have motion only down to the wave base, at a distance equal to half the wavelength.

Since the wavelength of tsunamis is typically about 120 miles (200 km), movement associated with the passage of the waves could be felt to a depth of 60 miles (100 km), much greater than the depth of the oceans. Tsunamis therefore are felt at much greater depths than ordinary waves, and the normally still, deep-ocean environment will experience sudden elliptical or back and forth motions, plus pressure differences, during the passage of tsunamis. These effects may be used with deep-ocean-bottom tsunami detectors to help warn coastal communities when tsunamis are approaching.

Many tsunamis are different from regular waves in that they may have highly irregular wave-train patterns. Some tsunamis have a high initial peak, followed by successively smaller wave crests, whereas other tsunamis have the highest crest located several crests behind the initial crest. The reasons for these differences are complex, but most are related to the nature of the triggering mechanism that formed the wave train. A splash or meteorite impact may create an initial large crest, whereas an undersea explosion may cause an initially small crest, followed by a larger one related to the interaction of the waves that fill the hole in the water column related to the explosion. Many variables contribute to the initial shape of the wave train, and each wave train needs to be examined separately to understand what caused its shape.

Different mechanisms of tsunami generation may form several sets of wave trains with different wavelengths. Longer-wavelength wave trains travel at higher speeds than shorter-wavelength wave trains, so the farther the tsunami travels from the source, the more spread out the waves of different wavelengths will become. This phenomenon is known as wave dispersion. The effect of dispersion is such that locations near the source will see complex waves where the short- and long-wavelength sets are superimposed, and these waves combine to make taller or shorter waves of each set as they crash into shore. Locations more distant from the tsunami source will first experience the fast-traveling, long-wavelength waves, and then later be hit by the shorter-wavelength (and -period) waves. The time difference between these different sets becomes greater with increasing distance from the source.

When tsunamis are traveling across deep-ocean water, their amplitudes are typically less than three feet (1 m), even though the wavelength may be more than 100 miles (160 km). A passenger on a ship would probably not notice even the largest of tsunamis if the ship was in the deep ocean.

Since tsunamis are essentially shallow-water waves when they travel across the open ocean, they will experience different amount of friction by different water depths and topographic features, such as submerged mountains, on the seafloor. The shallower the feature, the greater the friction, and the more it will slow the passage of the tsunami wave-front above that feature. Tsunamis are like other wave features—when they encounter objects that slow their travel, they bend around that object, and are said to be refracted. Refraction of tsunamis is quite common in the Pacific and Indian Oceans. In the Pacific, this phenomenon is typically seen when waves generated along the Pacific subduction zones travel to the center of the ocean and get refracted around the islands of the Hawaiian chain. The bending of tsunami wave-fronts around objects such as Hawaii can have two main effects on the wave energy—it can focus the energy in some locations where the wave fronts that bend around the object from either side merge and add together, or it can spread apart this energy and disperse it so that it is less intense. In the Pacific Ocean, the island of Hawaii tends to focus the energy from earthquake-generated tsunamis that form along the western coasts of North and South America on the island of Japan. This is one reason that Japan has endured so many tsunami events in history. Japan must accommodate tsunamis generated locally by earthquakes in its own vicinity, and the shape of the seafloor in the Pacific focuses the energy from distant earthquake-generated tsunamis onto this island nation. Tsunamis that are amplified in this way from distant earthquakes are known as teleseismic tsunamis. An example of the opposite effect, the defocusing of seismic energy is commonly afforded by the small island of Tahiti in French Polynesia. The seafloor topography of the Pacific commonly causes incoming tsunamis to be defocused or dispersed as the waves approach this island.

Encounter with Shallow Water

Waves with long wavelengths travel faster than waves with short wavelengths. Since the longer the wavelength the faster the wave in deep open water, tsunamis travel extremely fast across the ocean. Normal ocean waves travel at less than 55 miles per hour (90 km/hr), whereas many tsunamis travel at 375 to 600 miles per hour (800 to 900 km/hr), faster than most commercial airliners. The wave speeds slow down as the tsunamis encounter shallow water, typically in the range of 60–180 miles per hour (100–300 km/hr) across the continental shelves, and about 22 miles per hour (36 km/hr) at the shore. This slowing of the wave speed as it begins to encounter shallow water causes the waves at the back of the train to move faster than those in the front. When this occurs the wave must become taller and narrower to accommodate the waves moving into the same space from behind; thus as the tsunami moves from deep water into shallow waters, it becomes taller (larger amplitude), has a shorter distance between crests (shorter wavelength), and moves slower (velocity). In some cases many of the crests will merge and the troughs will disappear during this process, producing huge solitary waves, whose height from base to top is entirely above sea level.

When waves encounter shallow water, the friction of the seafloor along the base of the wave becomes greater than when the waves were traveling in deep water, causing them to slow down dramatically, and the waves effectively pile up on themselves as successive waves move into shore. This causes the wave height or amplitude to increase dramatically, sometimes 10 to 150 feet (3–45 m) above the normal stillwater line for tsunamis.

One of the main effects of the friction at the base of the tsunami as it enters shallow water is that the wave fronts tend to be strongly refracted, or bent, so that they approach land at less than 10° no matter what the original angle of approach to the shore was. This refraction occurs because the part of the wave that encounters shallow water first will be slowed down by the increased friction, whereas the other part of the wave still in deepwater will continue to move faster, until it catches up with the rest of the wave by being in the same water depth, then moves at the same rate. This effect bends tsunamis, like other waves, so that they hit most shoreline areas nearly head-on. Seafloor topography very close to the shore can modify this refraction, and either focus the energy into specific locations, or disperse it across the shoreline.

The friction at the base of the wave dissipates or takes some of the energy away from the tsunami. In most settings the amount of dissipation of energy by friction is minor (less than 3 percent), but in some cases where the continental shelf areas are very wide and narrow, the dissipation may be significant enough to reduce the tsunami threat to the region dramatically. Such is the case for the part of the northeast seas of China (Yellow Sea, Bohai, and related areas) where the water depth is quite shallow for many hundreds of miles, making the northeast coast of China much less susceptible to tsunamis than the southeastern coast, where the shelf area is deeper and narrower. Much of the east coast of the United States has a moderately wide and shallow shelf that is able to dissipate about 20 percent of the energy of most tsunamis by friction along the wave base. Areas that have narrow and steep continental shelves offshore are prone to the most severe tsunamis, since these areas do not have the ability to reduce the wave energy by friction.

Tsunami waves exhibit a phenomenon called diffraction when they enter bays through a narrow entrance. Diffraction occurs when energy moves or is leaked sideways along a wave crest, enabling the wave to grow along the wave front to fill the available area inside a wide bay that the wave has entered through a narrow opening. The wave front must enter through the narrow passage to the ocean, but then spreads across the bay as a longer wave. The process of dispersion moves energy from the initially high wave crest sideways, and in doing so takes energy away from the central area, decreasing the height of the wave. Thus, the dispersion of energy during the wave's entrance and spread into the harbor is a good thing, reducing the threat to areas inside bays with narrow entrances. An example of a bay with a shape that would disperse tsunami energy is San Francisco Bay. If a tsunami were to pass under the Golden Gate Bridge it would crash through the narrows there, but then spread, losing height and ferocity, as it moved into the Bay Area.

Amplification, the opposite effect of dispersion, occurs in some bays where the opening of the bay or estuary is wide, and the bay narrows progressively inland. Tsunamis that enter such treacherous waters will find their wave crests being amplified or increased in height, transferring energy along the wave crest as they are forced to become shorter lengthwise along the crests of the waves. There are many examples of tsunami disasters that occurred because the shape of the bay amplified the tsunami that would otherwise have been minor. A famous example of this effect is the 1964 tsunami that hit Crescent City, California, from the magnitude 9.2 earthquake in Alaska. Most areas along the California coast experienced a relatively minor tsunami (less than two feet, or half a meter in height), but the shape of the bay and seafloor at Crescent City amplified the wave until it consisted of a series of five tsunami crests. The fifth was a 21-foot- (6.3-m-) high crest that swept into downtown, washing away much of the waterfront district and killing 11 people.

When tsunamis strike the coastal environment, the first effect is sometimes a significant retreat or drawdown of the water level, whereas in other cases the water just starts to rise quickly. Since tsunamis have long wavelengths, it typically takes several minutes for the water to rise to its full height. Also, since there is no trough right behind the crest of the wave, on account of the very long wavelength of tsunamis, the water does not recede for a considerable time after the initial crest rises onto land. The rate of rise of the water in a tsunami depends in part on the shape of the seafloor and coastline. If the seafloor rises slowly, the tsunami may crest slowly, giving people time to outrun the rising water. In other cases, especially where the seafloor rises steeply, or the shape of the bay causes the wave to be amplified, tsunamis may come crashing in huge walls of water with breaking waves that pummel the coast with a thundering roar and wreaking utmost destruction.

Because tsunamis are waves, they travel in successive crests and troughs. Many deaths in tsunami events are related to people going to the shoreline to investigate the effects of the first wave, or to rescue those injured or killed in the initial crest, only to be drowned or swept away in a succeeding crest. Tsunamis have long wavelengths, so successive waves have a long lag time between individual crests. The period of a wave is the time between the passage of individual crests, and for tsunamis the period can be an hour or more. Thus, a tsunami may devastate a shoreline area and retreat, and then another crest may strike an hour later, then another, and another in sequence.

The specific shape of any shoreline has large effects on the tsunami height and the way it approaches the shoreline. The study of the effects of local coastal features on the tsunami is called morphodynamics. As the water from one wave crest retreats, it must move back to sea, and interact with the next incoming wave. Some of this water moves quickly sideways along the coast, setting up a new independent set of waves that oscillates up and down in amplitude along the coast, typically with a wavelength that is double that of the original tsunami. These secondary waves are called edge waves, and may be nearly as large as the original tsunami. When the following tsunami crests approach the shoreline, they may interact with a positive crest and produce a wave that is larger than the initial tsunami, or they may interact with a negative trough, and produce a smaller wave. These edge waves and local morphodynamics explain much of the variability of the height of tsunamis along some shorelines. In some locations the tsunami crest may be 30 feet

(10 m) high, while in other nearby areas it may only be six feet (2 m) high.

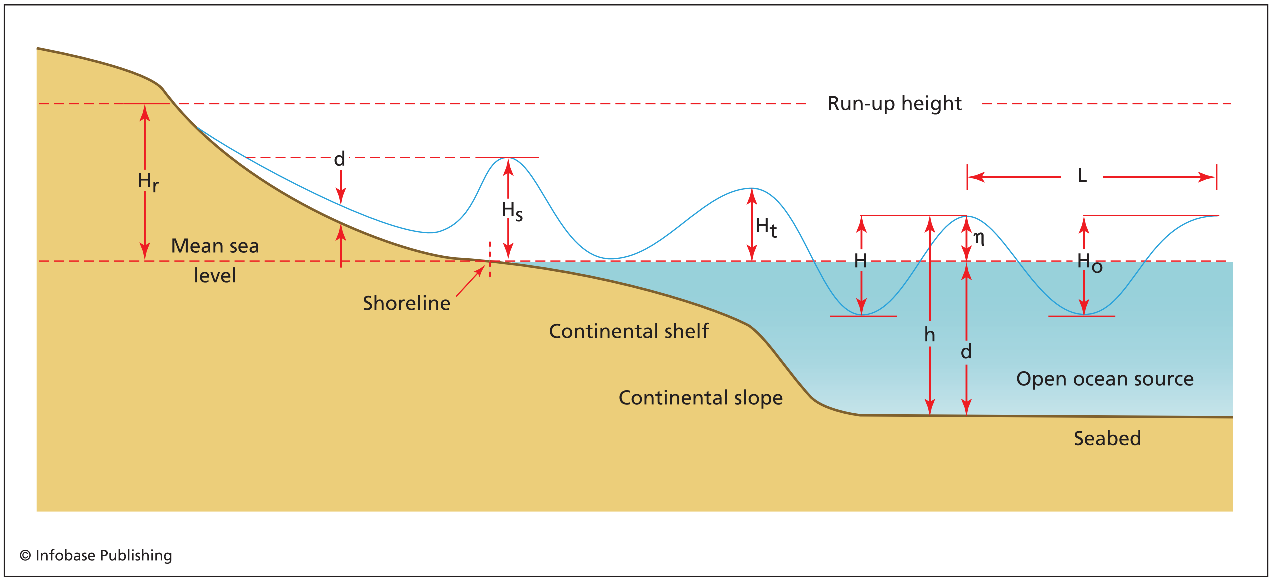
The name tsunami means *harbor wave* in Japanese, and the term describes another physical phenomenon of waves called resonance. When waves enter harbors or bays, they have a characteristic period that in many cases matches a natural harmonic frequency of that particular harbor. This means that many tsunamis enter a bay, and bounce back and forth across the harbor with the exact period that causes the wave to dramatically increase in height. The effect is similar to slowly moving a glass of water back and forth, and gradually increasing the speed until suddenly the waves in the glass start to become amplified and then leap out of the glass. This happens when the period of the wave equals that of the natural frequency of the glass. Many tsunamis that enter bays will resonate, or oscillate back and forth in the bay for 24 hours or more, causing disruption of activities for an extended period.

Tsunami Run-up

Run-up is the height of a tsunami above sea level at the farthest point it reaches on the shore. This height may be considerably different from the height of the wave where it first hits the shore, and is commonly twice that of the height of the wave at the shore. Run-up heights of 30 feet (10 m) are fairly common for tsunamis, while heights of 150–300 feet (45–90 m) are rare, and heights greater than this in the range of 300–1,700 feet (90–525 m) are very rare, but have been observed in the past hundred years. Many things influence the run-up of tsunamis, including the size of the wave, the shape of the shoreline, the profile of the water depth, diffraction, formation of edge waves that move along the coast, and other irregularities particular to individual areas. Some bays and other places along some shorelines may amplify the effects of waves that come in from a certain direction, making run-ups higher than average. These areas are called wave traps, and in many cases the incoming waves form a moving crest of breaking water, called a bore, that smashes into coastal areas with great force. Tsunami magnitudes are commonly reported using the maximum run-up height along a particular coastline.

When tsunamis approach the shore, the wave fronts pile up and the wave changes form from a sinusoidal wave to a solitary wave, with the entire wave form above sea level. These types of waves maintain their forms, and since the kinetic energy in the wave is evenly distributed throughout the wave, the waves lose very little energy as they approach the shore. Steep coastlines may experience larger run-ups, since they have the least amount of energy dissipation. The shape and angles of cliffs along the beach can also amplify tsunami heights, in some cases tripling the height of the wave at the shore. Embayments that become narrower inland may amplify waves, and in some bays it may take two or even several tsunami crests for the amplification process to reach a maximum. Refraction effects can increase tsunami run-up around promontories where narrow strips of land jut out into the sea.

In some cases, tsunamis are refracted around the shores of islands, or both sides of bays, producing large edge waves that move parallel to shore. These edge waves must merge on the back sides of islands,



Definition of tsunami run-up height. Note how this is higher than the wave height at the coast.

or in the ends of embayments, and in these locations particularly large run-ups have been recorded. Movement of edge waves around islands accounts for many of the large run-ups on the leeward sides of the Hawaiian Islands from the April 1, 1946, tsunami in Hilo, Hawaii, where many bays on the back sides of the islands experience run-ups almost as high as those facing the initial wave front. The 1992 Flores Island tsunami also saw many villages on the leeward sides (facing away from the wave front) of islands washed away by large tsunamis. These waves also formed by the waves being refracted around the islands, forming edge waves that combined to cause unusually large run-ups in specific locations. More than 2,000 people died when the 16–23-foot (5–7-m) waves washed into these villages on the back sides of the islands. Similarly, in a 1993 tsunami in Japan, the island of Okushiri focused the energy of a tsunami on the town of Hamatsumae lying behind the island. On July 12, a 100-foot (30-m) wave grew behind the island and washed into the town, killing 330 people.

Force of Tsunami Impact and Backwash

When tsunamis crash into coastal areas they are typically moving at about 22 miles per hour (35 km/hr). The speed as the wave moves inland changes dramatically, decreasing to a few miles per hour (several km/hr) over short distances, depending on the slope of the beach or shore environment and how much resistance the wave encounters from obstacles on shore. The force associated with a debris-laden wall of water 50–70 miles (80–120 km) wide moving inland at that speed is tremendous. As tsunamis impact the shoreline and move inland they rapidly pick up debris and move this with the wave front, and these objects smash into whatever is in the path of the water, destroying almost anything in the way. The force of the tsunami can be appreciated by considering the impact of a series of rocks thrown from a moving car, or a train hitting a building at 22 miles per hour (35 km/hr). After the first impact the force of the wave does not stop but keeps on pounding into the coast until the crest passes; then the water continues to move inland and remain high for 30, 40, 50 minutes or more before retreating back to sea. The force of the tsunami backwash can be just as strong, and in some cases stronger than the initial impact. Some waves take five minutes or more to move inland, and less than two minutes to wash back out to sea, so the outgoing velocity may be greater than the initial surge. The outgoing waves often take the loose debris from the destruction of the incoming wave with them, placing projectiles in the water for the next crest to launch when it moves inland.

Many tsunamis have been observed to form a thin wedge of turbulent water that shoots out in front of the wave crest with tremendous speed and force. These turbulent wedges of foamy debris-laden water do a lot of damage to buildings and vegetation just before the wave crest hits, and may be associated with much higher velocities of projectiles than found in the main wave. These wedges may form by the weight of the wave compressing air trapped in front of the wave and shooting this air-water-debris mixture out as the wave moves inland.

In many cases the area of land that is flooded by a tsunami is roughly equal to the area found beneath the wave crest when it is close to shore. Larger tsunamis flood larger areas. The amount of flooding is greatest for flat open areas such as mudflats, pastures, etc., where the wave can move uninterrupted inland. The amount of inland penetration decreases for areas that have forests, buildings, or other obstacles that slow the wave down. A moderate tsunami, about 30 feet (10 m) high, might penetrate a little less than a mile (1.6 km) inland in flat but developed coastal areas, half a mile (less than a kilometer) in a developed downtown city environment, and perhaps four miles (6 km) on an undeveloped open coast. Dense coastal forests are able to significantly decrease the amount of inland penetration, taking much of the energy of the wave away as it must snap and move the trees to move further inland. Large tsunamis, greater than 160 feet (50 m) tall, can move inland 5–7 miles (9–12 km), while great tsunamis can theoretically reach tens of miles (km) inland.

REDUCING THE THREAT FROM TSUNAMIS

As more and more people move to the coastline in the United States and worldwide, ways must be found to reduce the threat from tsunamis. Tsunamis will inevitably form in the world's oceans and strike many shorelines in the years to come, but they do not have to kill a quarter million people like the Indian Ocean tsunami of 2004. Zones of high tsunami risk need to be mapped, such as places that tend to amplify the waves leading to higher run-ups, and the public needs to be educated about the signs of an impending tsunami. It is important for the public to know not only how to recognize a tsunami, but what to do when one may be approaching. Different types of tsunami warning systems can be built, and new methods of building along coastlines to reduce tsunami damage should be encouraged.

Monitoring Tsunami Threats

Many countries around the Pacific cooperate in monitoring the generation and movement of tsunamis. The seismic sea wave warning system was established and became operational after the great 1946 tsunami that devastated Hilo, Hawaii, parts of Japan, and many other circum-Pacific coastlines. The seismic sea wave warning system and other tsunami warning systems generally operate by monitoring seismograms to detect potentially seismogeneic earthquakes, then monitor tide gauges to determine if a tsunami has been generated. Warnings are issued if a tsunami is detected, and special attention is paid to areas that have greater potential for being inundated by the waves.

It takes several different specialists to be able to warn the public of impending tsunami danger and reduce the threat from tsunamis. First, seismologists are needed to monitor and quickly interpret the earthquakes and determine which ones are potentially dangerous for tsunami generation. Second, oceanographers are needed to predict the travel characteristics of the tsunami. Coastal geomorphologists must interpret the shape of coastlines and submarine topography to determine which areas may be the most prone to being hit by tsunamis, and geologists are needed to search for any possible ancient tsunami deposits to see what the history of tsunami run-up is along specific coastlines. Finally, engineers are needed to try to modify coastlines to reduce the risk from tsunamis. Features such as sea walls and breakwaters can be built, and buildings can be sited in places that are outside of reasonable tsunami striking distance. Loss control engineers typically work with insurance underwriters to identify areas and buildings that are particularly prone to tsunami-related flooding.

Several detailed reports have described areas that are particularly prone to repeated tsunami hazards. The United States Army Engineer Waterways Experiment Station has produced several of these reports useful for city planners, the Federal Insurance Administration, and state and local governments.

The National Oceanic and Atmospheric Administration (NOAA) has been operating tsunami gauges in the deep ocean since 1986. These instruments must be placed on the deep seafloor (typically up to 1,500–2,000 feet [1,000 m] depth) and recovered and redeployed each year. Cables send the recordings from these instruments back to shore. The information derived from these tsunami gauges is used for tsunami warning systems and also used for planning coastal development, since the pressure changes associated with tsunami can be accurately recorded over long periods of time, and the history of tsunami heights in given areas assessed before coastal zones are further developed.

The NOAA runs Pacific Tsunami Warning Center in Honolulu. The United States Geological Survey also has been actively engaged in mapping tsunami hazard areas and establishing ancient tsunami run-up heights on coastlines prone to tsunamis, to help in predicting future behavior in individual areas. The results from these mapping programs are routinely presented to local government planning boards, to help in protecting people in coastal areas and assigning risks to development in areas prone to tsunamis.

Predicting Tsunamis

Great progress has been made in predicting tsunamis, both in the long term and in the short term, following tsunami earthquakes. Much of the long-term progress reflects recognition of the association of tsunamis with plate tectonic boundaries, particularly convergent margins. Certain areas along these convergent margins are susceptible to tsunami-generating earthquakes, either because of the types of earthquakes that characterize that region, or because thick deposits of loose unconsolidated sediments characteristically slide into trenches in other areas. Progress in short-term prediction of tsunamis stems from the recognition of the specific types of seismic wave signatures that are associated with tsunami-generating earthquakes. Seismologists are in many cases able to immediately recognize certain earthquakes as potentially tsunami-generating and issue an immediate warning for possibly affected areas.

Tsunamis are generated mainly along convergent tectonic zones, mostly in subduction zones. The motion of the tsunami-generating faults in these areas is typically at right angles to the trench axis. After many years of study, geologists have documented a relationship between the direction of the motion of the fault block and the direction toward which most of the tsunami energy (expressed as wave height) is directed. Most earthquakes along subduction zones move at right angles to the trench, and the tsunamis are also preferentially directed at right angles away from the trench. This relationship causes certain areas around the Pacific to be hit by more tsunamis than others, because there is a preferential orientation of trenches around the Pacific. Most tsunamis are generated in southern Alaska (the tsunami capital of the world), are directed toward Hawaii, and glance the west coast of the lower 48 states, whereas earthquakes in South America direct most of their energy at Hawaii and Japan.

Tsunami Hazard Zones and Risk Mapping

The USGS and other Civil Defense agencies have mapped many areas that are particularly prone to tsunamis. Recent tsunamis, historical records, and deposits of ancient tsunamis identify some of these areas. Many coastal communities, especially those in Hawaii, have posted coastal areas with tsunami warning systems, showing maps of specific areas prone to tsunami inundation. Tsunami warning signals are in place and residents are told what to do and where to go if the alarms are sounded. Residents and visitors in these areas must understand what to do in the event of a tsunami warning, and where the escape routes may be. If there is a local earthquake, landslide, or undersea volcanic eruption, there may be only minutes before a tsunami hits, so it is essential not to waste time if the tsunami warning sirens are sounded.

Tsunami Warning Systems

Tsunami warning systems have been developed that are capable of saving many lives by alerting residents of coastal areas that a tsunami is approaching their location. These systems are most effective for areas located more than 500 miles (750 km), or one hour away from the source region of the tsunami, but may also prove effective at saving lives in closer areas. The tsunami warning system operating in the Pacific Ocean basin integrates data from several different sources, and involves several different government agencies. The National Oceanic and Atmospheric Administration operates the Pacific Tsunami Warning Center in Honolulu, which includes many seismic stations that record earthquakes, and quickly sorts out those earthquakes that are likely to be tsunamogenic based on the earthquake's characteristics. A series of tidal gauges placed around the Pacific monitors the passage of any tsunamis past their locations, and if these stations detect a tsunami, warnings are quickly issued for local and regional areas likely to be affected. Analyzing all of this information takes time, however, so this Pacific-wide system is most effective for areas located far from the earthquake source.

Tsunami warning systems designed for shorter-term, more local, warnings are also in place in many communities, including Japan, Alaska, Hawaii, and many other Pacific islands. These warnings are based mainly on quickly estimating the magnitude of nearby earthquakes, and the ability of public authorities to rapidly issue the warning so that the population has time to respond. For local earthquakes, the time between the shock event and the tsunami hitting the shoreline may be only a few minutes. Anyone in a coastal area that feels a strong earthquake should take that as a natural warning that a tsunami may be imminent and leave low-lying coastal areas. This is especially important considering that approximately 99 percent of all tsunami-related fatalities have historically occurred within 150 miles (250 km) of the tsunami's origin, or within 30 minutes of when the tsunami was generated.

Knowing When a Tsunami Is Imminent

Anybody who is near the sea or in an area prone to tsunamis (as indicated by warning signs in places like Hawaii) needs to pay particular attention to some of the subtle and not so subtle warning signs that a tsunami may be imminent. First, there may be warning sirens in areas that are equipped with a tsunami warning system. If the sirens are sounded, it is imperative to move to high ground immediately. People in more remote locations may need to pay attention to the natural warning signs. Anyone on the shore who feels an earthquake should run for higher ground. A tsunami may hit within minutes, an hour or two, or not at all, but it is better to be safe than sorry. Tsunamis travel in groups with periods between crests that can be an hour or more, so there are likely to be several crests over a period of many hours. Many people have died when they returned to the beach to investigate the damage after the first crest passes. If the tsunami-generating earthquake occurred far away, there may not be any detectable ground motion before a tsunami hits, and residents of remote areas may not have any warning of the impending tsunami, except for the thunderous crash of waves right before it hits the beachface. In other cases, the water may suddenly recede to unprecedented levels right before it quickly rises up again in the tsunami crest. In either case, any one enjoying the beachfront needs to remain aware of the dangers. In general, the heads of bays receive the highest run-ups, and the sides and mouths record lower run-up heights. but this may vary considerably depending on the submarine topography and other factors.

Public Education and Knowing How to Respond

Communities situated in tsunami-prone areas need to educate their populace on how to respond in a tsunami emergency, especially how to follow directions of emergency officials and to stay away from the waterfront. People in low-lying areas should have planned routes to quickly seek high ground, such as by climbing a hill, or entering into a tall building designed to withstand a tsunami. Most important, people should know not to return to the seafront until they are instructed by authorities that it is safe to do so, because there may be more waves coming, spaced an hour or more apart.

Many United States and foreign agencies have completed exhaustive studies of ways to mitigate or reduce the hazards of tsunamis. For instance, the Japanese Disaster Control Research Center has worked with the Ministry of Construction to evaluate the effects of tsunamis on their coastal road network, to plan better for inundation by the next tsunami. They considered historical records of types of damage to the road systems (wash-outs, flooding, blockage by debris from destroyed homes and cars, etc.) and detailed surveys of the region to devise a plan of alternate roads to use during tsunami emergencies. They have devised a mechanism of communicating the immediate danger and alternate plans to motorists. Their system includes plans for the installation of multiple wireless electronic bulletin boards at key locations, warning motorists to steer away from hazardous areas. Similar studies have been undertaken by other agencies that deal with the coastal area, such as the Fisheries Agency. They have suggested building a series of levees, emergency gates, and cut-off facilities to maintain the fresh water supply to residents.

SUMMARY

Tsunamis are long-wavelength deep sea waves formed by the sudden displacement of large volumes of seawater. When these waves encounter shallow water, they may form huge breaking waves with walls of water tens or a hundred feet (tens of m) tall that slam ashore. Every few years some of these giant waves rise unexpectedly out of the ocean and sweep over coastal communities, killing thousands of people and causing millions of dollars worth of damage. Triggering mechanisms for tsunamis include earthquake-related displacements of the seafloor, submarine slumps and landslides that displace seawater, submarine volcanism, explosive release of methane gas from deep-ocean sediments, and asteroid impacts.

Tsunamis have wavelengths of 120 miles (200 km) or greater, periods of 1.6–33 minutes, and travel at speeds of 375–600 miles per hour (800–900 km/hr), compared to 55 miles per hour (90 km/hr) for normal wind-blown ocean waves. The effective wave base for tsunamis is therefore deeper than the ocean basins. Tsunamis feel friction from the deep ocean basins and are effectively refracted and reflected around the world's oceans. When tsunamis encounter shallow water they slow their forward velocity, and the waves behind the waves in the front move faster, pile up behind the first waves, and increase the amplitude of the waves crashing into the beach. Run-up is the height of the tsunami above sea level at the farthest point it reaches on shore. This height may be considerably different from the height of the wave where it first hits the shore, and is commonly twice that of the height of the wave at the shore. When tsunamis crash into coastal areas they are commonly moving at 22 miles per hour (35 km/hr). The force associated with the tsunami hitting the shoreline is tremendous, as it consists at this point of a debris-laden wall of water, 50–70 miles (80–120 km) wide, moving steadily inland like an unstoppable derailed locomotive. Since tsunamis are long-wavelength waves, they continue to move inland and remain high for 30–50 minutes before rapidly retreating with a force that may exceed the force of initial incursion. Tsunamis travel in wave trains, so this process may repeat itself six or seven times over the course of many hours, with the second or third wave often being the tallest.

The threat to coastal communities from tsunamis can be reduced. First, the historical record of tsunamis in any area should be determined through geological mapping, and areas at greatest risk need to be identified. Residents and visitors to these areas should know escape routes, and what to do in the event of a tsunami emergency. Most ocean basins now have seismic sea wave warning systems installed, allowing scientists to monitor triggering mechanisms (such as earthquakes) and sea-bottom pressure and motion detectors that tell of passing tsunamis. Warnings can be issued to coastal communities when it is determined that a tsunami may be approaching. Public education programs should teach the public about the hazards of tsunamis, since many of the deaths from tsunamis have been preventable. For instance, many people have perished because they have returned to coastal areas after the first wave crest has passed, not realizing that the second or third crest may be the largest, and many crests hit hours after the first wave crashes ashore. Areas in the United States most at risk include the Pacific Northwest, where a potentially tsunamogenic forearc zone is located close to densely populated coastal areas. Any large earthquake in this area could form a tsunami that crashes in coastal communities within minutes of the earthquake, barely giving residents enough time to evacuate to higher ground. Most other coastal areas of the United States also have some risk of tsunamis, so all coastal residents need to be aware of the risks and how to respond in a tsunami emergency.

See also BEACHES AND SHORELINES; EARTHQUAKES; GEOLOGICAL HAZARDS; PLATE TECTONICS; TSUNAMIS, HISTORICAL ACCOUNTS.

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tsunamis, historical accounts Tsunamis have taken hundreds of thousands of lives in the past few hundred years, and some of the larger tsunamis have caused millions to billions of dollars in damage. The table "Historical Tsunamis" lists the more significant tsunamis that are well documented in recorded history.

EARTHQUAKE-INDUCED TSUNAMIS

The most common type of tsunamis are those generated by earthquakes that displace the seafloor. The majority of these are initiated at convergent margins such as along trench-forearc accretionary wedges, where large displacements of the seafloor are relatively common. Most convergent margins are located around the edges of the Pacific Ocean, so it follows that most tsunamis strike the margins of the Pacific Ocean. Many others are generated along the convergent margins in the Indonesian region, including the devastating December 26, 2004, Indian Ocean tsunami.

December 26, 2004, Indian Ocean Tsunami

One of the deadliest natural disasters in history unfolded on December 26, 2004, when a great undersea earthquake with a magnitude of 9.0 triggered a tsunami that devastated many coastal areas of the Indian Ocean, killing an estimated 283,000 people. The Sumatra-Andaman earthquake had an epicenter located 100 miles (160 km) off the west coast of Sumatra, and struck at 7:58 A.M. local time. This was a very unusual earthquake, in that the rupture (and quake) lasted between eight and 10 minutes, one of the longest times ever recorded for an earthquake. The hypocenter, or point of first energy release, was located 19 miles (30 km) below sea level, and the rupture length of the fault extended to a remarkable 750 miles (1,200 km) along the coast of Sumatra. Shaking from the earthquake was felt as far away as India, Thailand, Singapore, and the Maldives. The energy released by this earthquake was so great that it set the whole planet into a set of slow oscillations where all locations on the planet were vibrating back and forth by 8–12 inches (20–30 cm) initially, with a force roughly equivalent to the attraction between the Earth and Moon. The surface waves from the earthquake also traveled around the planet, producing a vibration of at least one-third of an inch (1 cm) everywhere on the planet. These vibrations gradually diminished in intensity over a period of a week, until they became so small that they were difficult to measure. The amount of energy released by this earthquake alone was roughly one-eighth of the energy released by all earthquakes on the planet in the past 100 years.

The tectonic setting of the Sumatra-Andaman earthquake was in the forearc of the active convergent margin between the Indian-Australian plate and the Burma plate of Eurasia. Oceanic crust of the Indian-Australian plate is being subducted beneath Sumatra and Indonesia at about two inches (6 cm) per year, forming a complex of volcanoes and active fault zones. The December 26, 2004, Sumatra-Andaman earthquake had characteristics that were extremely favorable for producing a large tsunami. A huge section of the forearc, 750 miles (1,200 km) long, was pushed upward and sideways by 50 feet (15 m), displacing a vast amount of water and sending it across the Indian Ocean as a giant tsunami. This displacement took place in two stages. First a 250-mile- (400-km-) long by 60-mile- (100-km-)

HISTORICAL TSUNAMIS

Location	Year	Number of Deaths
Indian Ocean	2004	> 283,000 dead across region
Santorini	1500 B.C.E.	devastation of Mediterranean
Eastern Atlantic	November 1, 1755	60,000 dead in Lisbon, estimated 100,000 total
Messina, Italy	1908	70,000 dead
Taiwan	May 22, 1782	50,000 dead
Krakatau	August 27, 1883	36,500 dead
Nankaido, Japan	October 28, 1707	30,000 dead
Sanriku, Japan	June 15, 1896	27,122 dead
Nankaido, Japan	September 20, 1498	26,000 dead
Arica, Chile, Peru	August 13, 1868	25,674 dead
Sagami Bay, Japan	May 27, 1293	23,024 dead
Guatemala	February 4, 1976	22,778 dead
Lima, Peru	October 29, 1746	18,000 dead
Bali, Indonesia	January 21, 1917	15,000 dead
Unzen, Japan	May 21, 1792	14,524 dead
Ryukyu, Japan	April 24, 1771	13,486 dead
Bali, Indonesia	November 22, 1815	10,253 dead
Guangzhou, China	May 1765	10,000 dead
Moro Bay, Philippines	August 16, 1976	8,000 dead
Honshu, Japan	March 2, 1933	3,000 dead
Indonesia	December 12, 1992	2,000 dead
Chile	May 22, 1960	2,231 known dead/missing, estimated 10,000 dead
Aleutians	April 1, 1946	150 in Hawaii, $25 million damage
Alaska	March 28, 1964	119 dead in California, $104 million damage
Nicaragua	September 2, 1992	170 dead
Indonesia	December 2, 1992	137 dead

wide rupture formed, ripping the rocks of the seafloor at a rate of 1.7 miles per second (2.8 km/sec), or in other words, at 6,300 miles per hour (10,000 km/hr). This rupture not only occurred rapidly, but represents the biggest rupture known to have ever been created by a single earthquake. After a break of less than two minutes, the rupture continued to propagate northward from the Aceh area at a slower rate (1.3 miles per second, or 2.1 km/sec) for another 500 miles (800 km) toward the Andaman and Nicobar Islands. Displacements of the seafloor changed the capacity of the Indian Ocean basin to hold water, slightly raising global sea levels by about 0.03 inch (0.01 cm).

Submarine sonar surveys of the seafloor by the British Navy vessel H.M.S. *Scott* revealed that several huge, fault-related submarine ridges collapsed during the earthquake, creating submarine landslides, some as large as 7 miles (10 km) across. The amount that these contributed to the formation of the tsunami is not known, but certainly less than the huge displacement of the entire seafloor of the forearc.

The vertical component of motion of the seafloor during the earthquake is estimated to have displaced about seven cubic miles (30 km^3) of seawater, producing a tsunami that radiated outward from the entire 750-mile- (1,200-km-) long rupture area, eventually reaching most of the world's oceans including the Pacific, Atlantic, and even the Arctic Ocean. The tsunami continued to travel around the Earth for days, with very small amplitudes.

Thousands of aftershocks followed the main earthquake for days and months after the main event, gradually decreasing in strength and frequency. The largest of these was a magnitude 8.7 event that occurred on March 28, 2005, in virtually the same location along the same fault, with events of up to magnitude 6.7 continuing for more than four months after the main earthquake. The distribution of aftershocks greater than magnitude 4 outlines an area beneath the forearc of the Sumatra-Andaman arc that moved or slipped as a result of the earthquake. The slipped area is roughly the size of the state of California.

The amount of energy that was released in the December 26, 2004, Sumatra earthquake is staggering. Estimates vary between energy equivalents of 250–800 megatons of TNT, or the amount of energy consumed within the entire United States over 3–11 days. This energy caused some interesting effects. First, the change in the shape of the Earth caused by the displacement changed the length of the day by a minute amount (2.58 microseconds). However, this effect is already worn off since the tidal friction of the moon increases the length of the day by about 15 microseconds per year. The change in mass distribution also changed the amount the Earth wobbles about its rotational axis by about an inch (2.5 cm), but since the natural wobble is about 50 feet (15 m), this is not a large amount and will be evened out by future earthquakes.

In addition to triggering one of the worst tsunami disasters of history, the December 26, 2004, Sumatra earthquake awakened the dormant volcano of Mount Talang, which erupted in Aceh Province in April 2005. This is one of the rare cases where energy from an earthquake can convincingly be shown to have initiated other geologic activity.

The tsunami from the December 26 earthquake was unprecedented in the amount of observation that was possible from satellites. The satellite data were not analyzed until after the event, and the satellites were therefore not used to help provide a warning to areas about to be hit by the tsunami, but the results show that it is possible to develop a satellite-based tsunami warning system. Radar satellites showed that while in deep water, in the middle of the Indian Ocean, the tsunami had a maximum height of only 2 feet (60 cm) and that the wave rose to enormous height when it moved into shallow water. For instance, the wave was more than 80 feet (24 m) high as it approached much of Aceh Province in Indonesia and rose to 100 feet (30 m) or more in some places as it moved inland. In some places the wave moved inland by more than 1.25 miles (2 km).

People flee as tsunami crashes at Koh Roya, part of Thailand's territory in the Andaman Islands, December 26, 2004. *(John Russell/AFP/Getty Images)*

Although the energy of the tsunami was much less than that of the earthquake, it still had a remarkably high energy equivalent of about five megatons of TNT. For comparison, this is more than double the amount of energy released by all the bombs and explosions (including the atomic bombs) in all of World War II.

Since the fault that produced the December 26 earthquake and tsunami was oriented nearly north-south, and the motion of the upper plate was up and to the west, most of the energy of the tsunami was focused into an east-west direction. Therefore the biggest tsunami waves moved westward from the 750-mile- (1,200-km-) long fault rupture, while smaller waves moved out in all directions. Many areas along the coast of northern Indonesia were hit quickly, less than 15 minutes from the initial earthquake, while it took the waves 90 minutes to two hours to reach the southern end of India and Sri Lanka. The tsunami hit parts of Somalia several hours later, and swept down the African coast until it struck South Africa about 16 hours after the quake with a crest five feet (1.5 m) high. Tidal stations in Antarctica recorded a wave three feet (1 m) high, with oscillations lasting for a couple of days after the first wave. The energy from the wave next moved into the Pacific and Atlantic Oceans. Some unusual focusing of the wave energy may have occurred, perhaps by the mid-ocean–ridge system, since some of the waves that hit the west coast of Mexico were 8.5 feet (2.6 m) high.

The Indian Ocean tsunami was particularly tragic because there was no tsunami warning system in place in the Indian Ocean, and most victims were taken by total surprise when the tsunami struck their areas. Even though the wave took hours to move around the ocean, there was not even a simple telephone communication network set up to alert residents of one coastal community that others had just perished in a tsunami, and the tsunami was moving their way. Such a simple warning system could have saved tens of thousands of lives. Since the tragedy of December 26, 2004, countries of the Indian Ocean have worked with the United Nations and other countries to establish a tsunami warning system that includes not only the Indian Ocean but also the Atlantic and Caribbean.

In most places the tsunami struck as a series of waves after an initial retreat of the sea, followed by a large crest moving ashore. There were about 30 minutes between each wave crest that rose into coastal areas. In most places the third wave was the largest, although many smaller tsunami crests continued to strike throughout the day. In a few locations people recognized early warning signs of the tsunami and successfully evacuated to safety. The most famous case is that of 10-year-old British citizen Tilly Smith, who paid attention to her studies about tsunamis in school and knew that when the waters on the beach rapidly retreat it is a sign of an impending tsunami. Tilly frantically warned her parents, who led an evacuation of the beach, saving many lives. Likewise, a Scottish science teacher named John Chroston recognized similar warning signs in a bay north of Phuket beach on Indonesia, and took a busload of tourists away from the beach front, saving lives. Some native communities also recognized early warning signs and retreated to safety. For instance, islanders on Simeulue, near the epicenter, fled away from the coast after they felt the initial earthquake, undoubtedly saving many lives. In some of the more puzzling responses to precursory phenomena, it is reported that elephants and other animals on some Indian Ocean islands of the Maldives chain south of India fled inland before the tsunami struck. Elephants have very astute hearing and may have felt the ground shaking from the approaching tsunami, so ran in fear into the dense forest.

Many countries in southeast Asia have developing economies and often sacrifice environmental concerns to advance economic development. To this end, some of these countries including Indonesia have been promoting the development of the shipping industry and the growth of shrimp farming in coastal regions. Many coral reefs have been blown up and coastal mangrove forests destroyed to let these industries grow faster. In other places coastal sand dunes have been removed to enhance growth of the coastal region. All of these natural ecosystems are fragile coastal systems that not only preserve habitats for a diverse set of species but also serve as a powerful shield from the force of incoming tsunamis. In areas where the reefs and forests were preserved, for instance the Surin Island chain off Thailand, the force of the tsunami was broken by these natural barriers. In other places, where these barriers have been removed, the waves crashed ashore with much greater force, killing those who would seemingly benefit by the destruction of their natural protective barrier. Many governments began to realize the value of these natural barriers after the tsunami and may make efforts to reverse, stop, or slow their destruction.

1755 Eastern Atlantic Tsunami

Tsunamis do not regularly strike Atlantic regions, with only about 10 percent of all tsunamis occurring in the Atlantic Ocean. A few tsunamis have been associated with earthquakes in the Caribbean region, such as in 1867 in the Virgin Islands, 1918 in Puerto Rico, and on June 6, 1692, when 3,000 people were killed by a tsunami that leveled Port Royal, Jamaica. The most destructive historical tsunami to hit the Atlantic region struck on November 1, 1755. Lisbon, Portugal, was the worst hit because it was near the epicenter of the earthquake that initiated the tsunami. At least three large waves, each ranging in height from 14 to 40 feet (4–12 m), struck Lisbon in quick succession, killing at least 60,000 people in Lisbon alone. England was hit by waves 6–10 feet (2–3 m) in height, and the tsunami even affected the Caribbean region, hitting Antigua with 12-foot (4 m) waves, and waves more than 20 and 15 feet (6 and 5 m) respectively in height swept Saba and St. Martin.

The Lisbon-Eastern Atlantic tsunami was generated by a large earthquake whose epicenter was located about 60 miles (100 km) southwest of Lisbon, probably on the boundary between the European and Azores-Gibraltar plates. The earthquake had an estimated magnitude of 9.0, and the shaking lasted for 10 minutes. During this time, three exceptionally large jolts occurred, causing massive destruction in Lisbon and the Moroccan towns of Fez and Mequinez. Most of Europe and Scandinavia reported seiche waves from lakes and inland water bodies.

The earthquake caused extensive damage in the city of Lisbon, toppling many buildings and causing widespread and uncontrolled fires in the city. In fear, many residents ran to the city docks in the harbor and on the Tagus River. As the buildings continued to collapse and the fire raged through the city, driving much of the population of 275,000 people to the waterfront, the worst part of this disaster was about to unfold. About 40–60 minutes after the massive earthquake, residents of Lisbon watched from the docks as the water rapidly drained out of the harbor, as if someone had pulled the plug in the bottom of a bathtub. A few minutes later a massive wall of water 50 feet (15 m) high swept up the harbor and over the docks, and then swept more than 10 miles (16 km) upriver. The tsunami was associated with a powerful backwash that dragged tens of thousands of people, bodies, and debris into the harbor. Two more giant waves rushed into the city an hour apart, and killed more of the terrified residents trapped between raging tsunami waves and a city crumbling under the forces of fire and earthquake aftershocks. About 60,000 people, nearly a quarter of the city's population, perished in the tsunami.

The November 1, 1755, earthquake caused extensive damage across the eastern Atlantic Ocean, with tsunamis sweeping the coasts of North Africa, Portugal, Spain, France, and the British Isles, and even islands in the Caribbean were affected. The tsunami moved inland by 1.5 miles (2.5 km) across low-lying areas of Portugal, and run-up heights around Portugal locally reached 65–100 feet (20–30 m) above sea level. Southern Portugal was the worst hit, where medieval fortresses and towns were destroyed or suffered heavy damage. The waves washed over the ancient walled city of Lagos, whose walls are anchored 36 feet (15 m) above sea level. The walls reduced the force of the waves, but the city was flooded, and the water had to drain out of the narrow city gates. The initial wave was followed by at least 18 secondary crests in southern Portugal, each adding damage upon the effects of the previous wave.

Western Europe was strongly hit by the tsunami as it spread northward. The south coast of England saw massive waves that tore up the coastal muds and sandbars, and the waves swept the shores of the Bay of Biscay. Boats in the North Sea were ripped from their moorings. The English Channel was swept by waves 10–13 feet (3–4 m) high at high tide, followed by even higher waves that oscillated every 10–20 minutes in the channel over the next five hours. The Azores, located offshore from Portugal, were hit by 50-foot (15-m) waves that raced across the Atlantic to the eastern seaboard of North America. Caribbean islands were hit by tsunamis with run-up heights in the range of 20–25 feet (6–7.5 m), with the worst hit areas reported to be St. Martin and Saba. Elsewhere in the Caribbean, 10–15-foot (3–4-m) waves were reported to have oscillated every five minutes for about three hours, affecting many harbor and coastal areas.

The 1992 Flores, Indonesia, Tsunami

One of the more deadly tsunamis in recent history hit the island of Flores, located in Indonesia several hundred miles from the coast of northern Australia near the popular resort island of Bali. The tsunami hit on December 12, 1992, and was triggered by a magnitude 7.9 earthquake, with the earthquake faulting event lasting for a long 70 seconds. The tsunami had run-up heights of 15 to 90 (4–27 m) feet along the northeastern part of Flores Island, where more than 2,080 people were killed and at least another 2,000 injured. Large amounts of sediment slumped underwater on the north side of the island during the earthquake, generating the unusually large and destructive tsunami.

Flores is an island located above the subduction zone where the Indian-Australian plate is being pushed beneath the Eurasian plate, along a convergent boundary. This subduction zone produces some of the largest earthquakes and tsunamis in the world, including the December 24, 2004, massive Indian Ocean tsunami. The earthquake that generated the Flores tsunami had its epicenter near the coast, and produced subsidence of 1.5–3.5 feet (0.5–1.0 m). Unlike most other tsunami-generating earthquakes in this part of the world, this earthquake was located on the back-arc side of the island, away from the trench and forearc. The type of fault that forms on the back side of the arc is called a back-thrust, which is what slipped producing the Flores tsunami.

There was very little warning time for the residents of Flores Island, because the epicenter of the earthquake that generated the tsunami was only 30 miles (50 km) off the northern coast of the island. The first waves hit less than five minutes after the initial earthquake shock, with five or six individual waves being recorded by residents in different places. Many places recorded three large waves, the first one preceded by a rapid withdrawal of water from the coast, then the wave arrived as a wall of water. In most locations the second wave was the largest, with run-up heights typically between 6–16 feet (2–5 m). However, run-up heights in the village of

TSUNAMI NIGHTMARE

One of the worst natural disasters of the 21st century unfolded on December 26, 2004, following a magnitude 9.0 earthquake off the coast of northern Sumatra in the Indian Ocean. The earthquake was the largest since the 1964 magnitude 9.2 event in southern Alaska and released more energy than all the earthquakes on the planet in the last 25 years combined. During this catastrophic earthquake, a segment of the seafloor the size of the state of California, lying above the Sumatra subduction zone trench, suddenly moved upward and seaward by more than 30 feet (9 m). The sudden displacement of this volume of undersea floor displaced a huge amount of water and generated the most destructive tsunami known in recorded history.

Within minutes of the initial earthquake a mountain of water more than 100 feet (30 m) high was ravaging northern Sumatra, sweeping into coastal villages and resort communities with a fury that crushed all in its path, removing buildings and vegetation and in many cases eroding shoreline areas down to bedrock, leaving no traces of the previous inhabitants or structures. Similar scenes of destruction and devastation rapidly moved up the coast of nearby Indonesia, where residents and tourists were enjoying a holiday weekend. Firsthand accounts and numerous videos made of the catastrophe reveal similar scenes of horror, where unsuspecting tourists and residents were enjoying themselves in beachfront playgrounds, resorts, and villages and reacted as large breaking waves appeared off the coast. Many moved toward the shore to watch the high surf with interest, then ran in panic as the sea rapidly rose beyond expectations, and walls of water engulfed entire beachfronts, rose above hotel lobbies, and washed through towns with the force of Niagara Falls. In some cases the sea retreated to unprecedented low levels before the waves struck, causing many people to move to the shore to investigate the phenomenon; in other cases, the sea waves simply came crashing inland without warning. Buildings, vehicles, trees, boats, and other debris were washed along with the ocean waters, forming projectiles that smashed at speeds of up to 30 miles per hour (50 km/hr) into other structures, leveling all in their paths, and killing more than a quarter million people.

The displaced water formed a deep-water tsunami that moved at speeds of 500 miles per hour (805 km/hr) across the Indian Ocean, smashing within an hour into Sri Lanka and southern India, wiping away entire fishing communities and causing additional widespread destruction of the shore environment. Ancient Indian legends speak of villages that have disappeared into the sea, stories that many locals now understand as relating times of previous tsunamis, long since forgotten by modern residents. South of India lie many small islands including the Maldives, Chagos, and Seychelles, many of which have maximum elevations of only a few to a few tens of feet (1–10 m) above normal sea level. As the tsunami approached these islands, many wildlife species and primitive tribal residents fled to the deep forest, perhaps sensing the danger as the sea retreated and the ground trembled with the approaching wall of water. As the tsunami heights were higher than many of the maximum elevations of some of these islands, the forest was able to protect and save many lives in places where the tsunami caused sea levels to rise with less force than in places where the shoreline geometry caused large breaking waves to crash ashore.

Several hours later the tsunami reached the shores of Africa and Madagascar, and though its height was diminished to less than 10 feet (3 m) with distance from the source, several hundred people were killed by the waves and high water. Kenya and Somalia were hit severely, with harbors experiencing rapid and unpredictable rises and falls in sea level and many boats and people washed to sea. Villages in coastal eastern Madagascar, recently devastated by tropical cyclones, were hit by large waves, washing homes and people into the sea, and forming new coastal shoreline patterns.

The tsunami traveled around the world with progressively decreasing height with time, as measured by satellites and ocean bottom pressure sensors more than 24 hours later in the North Atlantic and Pacific Oceans. Overall, more than 283,000 people perished in the December 26th Indian Ocean tsunami, though many might have been saved if a tsunami warning system had been in place in the Indian Ocean. Tsunami warning systems have been developed that are capable of saving many lives by alerting residents of coastal areas that a tsunami is approaching their location. These systems are most effective for areas located more than 500 miles (805 km), or one hour away, from the source region of the tsunami but may be effective at saving lives in closer areas. The tsunami warning system operating in the Pacific Ocean basin integrates data from several different sources and involves several different government agencies. The National Oceanic and Atmospheric Administration operates the Pacific Tsunami Warning Center in Honolulu. It includes many seismic stations that record earthquakes and quickly sorts out those earthquakes that are likely to be tsunamogenic based on the earthquake's characteristics. A series of tidal gauges placed around the Pacific monitors the passage of any tsunamis past their locations, and if these stations detect a tsunami, warnings are quickly issued for local and regional areas likely to be affected. Analyzing all of this information takes time, however, so this Pacific-wide system is most effective for areas located far from the earthquake source.

Tsunami warning systems designed for shorter-term, more local, warnings are also in place in many communities, including Japan, Alaska, Hawaii, and many other Pacific islands. These warnings are based mainly on quickly estimating the magnitude of nearby earthquakes and the ability of public authorities to rapidly issue the warning so that the population has time to respond. For local earthquakes, the time between the shock event and the tsunami hitting the shoreline may be only a few minutes. Anyone in a coastal area that feels a strong earthquake should take that as a natural warning that a tsunami may be imminent, and should quickly leave low-lying coastal areas. This is especially important considering that approximately 99 percent of all tsunami-related fatalities have historically occurred within 150 miles (250 km) of the tsunami's origin, or within 30 minutes of when the tsunami was generated.

The magnitude 9.0 Sumatra earthquake that caused the Indian Ocean tsunami was detected by American scientists who tried to warn countries in soon-to-be-affected regions that a tsunami might be approaching. However, despite efforts by some scientists over the past few years, no systematic warning system was in place in the Indian Ocean. Initial cost estimates for a crude system were about 20 million dollars, deemed too expensive by poor nations who needed the funds for more obviously pressing humanitarian causes. When the earthquake struck on a Sunday, scientists who tried calling and e-mailing countries and communities surrounding the Indian Ocean to warn them of the impending disaster typically found no one in the office and no systematic list of phone numbers of emergency response personnel. Having a simple phone-pyramid list could have potentially saved tens of thousands of lives. Indian Ocean communities are now establishing a regional tsunami warning system.

The areas in the United States at greatest risk for the largest tsunami are along the Pacific coast, including Hawaii, Alaska, Washington, Oregon, and California. Most of the future tsunamis in these regions will be generated in subduction zones in Alaska, along the western and southwestern Pacific, and most frighteningly, along the Cascadia subduction zone in northern California, Oregon, and Washington. This region has experienced catastrophic tsunamis in the past, with geologists recently recognizing a huge wave that devastated the coast about 300 years ago. The reason this area has the present greatest risk in the United States for the largest loss of life and destruction in a tsunami is that it is heavily populated (unlike Alaska), and coastal areas lie very close to a potentially tsunami-generating subduction zone. Tsunamis travel faster than regular wind-generated waves, at close to 500 miles per hour (800 km/hr), so if the Cascadia subduction zone were to generate a tsunami, coastal areas in this region would have very little time to respond. If distant subduction zones generate a tsunami, the Pacific tsunami warning system could effectively warn coastal areas hours in advance of any crashing waves. However, a large earthquake in the Cascadia subduction zone would immediately wreak havoc on the land by passage of the seismic waves, then minutes to an hour later, potentially send huge waves into coastal Washington, Oregon, and California. There would be little time to react. It is these regions that need to invest most in more sophisticated warning systems, with coastal defenses, warning sirens, publicized and posted evacuation plans, and education of the public about how to behave (run and stay on high ground) in a tsunami emergency. Other coastal areas should initiate ocean basin–wide warning systems, install warning sirens, and post information on tsunami warnings and evacuation plans. Finally, the nation's general public should be better educated about how to recognize and react to tsunamis and other natural geologic hazards.

What are the lessons to be learned from the tragic Indian Ocean tsunami? People who are near the sea or in an area prone to tsunamis (as indicated by warning signs in places like Hawaii), need to pay particular attention to some of the subtle and not so subtle warning signs that a tsunami may be imminent. First, there may be warning sirens in an area that is equipped with a tsunami warning system. If the sirens sound an alert, do not waste time—run to high ground immediately. People in more remote locations may need to pay attention to the natural warning signs. Anyone who feels an earthquake while on the coast should run for higher ground. There may only be minutes before a tsunami hits, or maybe an hour or two, or never, but it is better to be safe than sorry. It is important to remember that tsunamis travel in groups, with periods between crests that can be an hour or more, so do not go back to the beach to investigate the damage after the first crest passes. If the tsunami-generating earthquake occurred far away, and there is no ground motion in the area, there may not be any warning of the impending tsunami, except for the thunderous crash of waves as it rises into the coastal area. In other cases, the water may suddenly recede to unprecedented levels right before it quickly rises up again in the tsunami crest. In either case, anyone enjoying the beach needs to remain aware of the dangers. Campers should pick a sheltered spot where the waves might be refracted and not run up so far. In general, the heads of bays receive the highest run-ups, and the sides and mouths record lower run-up heights. But this may vary considerably, depending on the submarine topography and other factors.

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Riang-Kroko were amplified to an astounding 86 feet (26.2 m), explaining why 137 of the 406 residents of the village were killed. Another hard-hit area was Babi Island, located three miles (5 km) offshore from Flores. The tsunami approached the island from the northeast and refracted around the island, where the edge waves met on the southwest corner and combined to produce a larger wave with run-up heights of 24 feet (7.2 m). The first, direct wave from the tsunami had a run-up velocity of 3.2 feet per second (1 m/sec), whereas the wave produced by the combined edge waves had a faster run-up velocity of up to 10 feet per second (3 m/sec). The island had 1,093 inhabitants, and 263 were washed away and drowned by the tsunami.

The residents of Flores were unaware that they lived in a tsunami hazard area, and they did not connect the ground shaking with possible sea hazards. Therefore, no warnings were issued and nobody fled the coastal areas after the quake. The villagers had built their homes and villages right along the coastline not far above the high-tide line, further compounding the threat. Many of the homes were made of bricks, but even these relatively strong structures were washed away by the powerful tsunami. In some cases, the concrete foundations of the basement moved many tens of feet inland as coherent blocks as the tsunami rushed across the area, with its associated strong currents. In this way, the tsunami made a less-than-subtle suggestion about where the safe building zone should begin. When the tsunami receded, 2,080 people were dead, 28,118 homes were washed away, and thousands of other structures were leveled. In many cases only white wave-washed beaches remained where there were once villages with populations of hundreds of people. Houses, furniture, clothing, animals and human remains were scattered through the forests behind the villages.

The Flores tsunami also caused severe coastal erosion, including cliff collapse and the scouring of coral reef complexes. Forests, brush, and grasses were removed, leaving vegetated hill tops and barren areas along the lower slopes of the coastal hills. Thick deposits of loose sediment were both moved inland and also redeposited as sheets of sediment in deeper water by the tsunami backwash, causing an overall sudden erosion of the land. Some large coral reef boulders, up to 4 feet (1 m) in diameter were moved inland many hundreds of feet (100 m) from the shoreline.

1992 Nicaragua Tsunami

The west coast of Nicaragua and Central America is a convergent margin where oceanic crust of the Cocos plate (a small plate attached to the Pacific Ocean plate) is being subducted beneath the western edge of the Caribbean plate. A volcanic arc with active volcanoes, earthquakes, and steep mountains has formed above this convergent margin subduction zone. The area is prone to large earthquakes in the forearc and to explosive volcanic eruptions and also suffers from many hurricanes, landslides, and other natural disasters.

On September 1, 1992, a relatively small (magnitude 7) earthquake centered 30 miles (50 km) off the coast of Managua, Nicaragua, generated a huge tsunami that swept across 200 miles (320 km) of coastline, killing 170 people and making 14,500 more homeless. This tsunami was generated by a tsunamogenic earthquake that ruptured near the surface, with a shallow focus of only 28 miles (45 km). The earthquake struck in an area where thick sediments have been subducted and are now plastered along the interface between the downgoing oceanic plate and the overriding continental plate of Central America. It has been suggested that these sediments lubricated the fault plane and caused the earthquake to rupture slowly and last a particularly long time, generating an unusually large tsunami for an earthquake of this size. After the fault plane initially slipped at depth, the rupture propagated outward and to the surface at a speed of 0.5–1 mile per second (1–1.5 km/sec), with the movement lasting for two minutes. The slow speed of the movement of the ground in this earthquake made the motion barely perceptible to people on the surface, but it was the perfect speed for effectively moving large volumes of water as the seafloor was displaced. Slow earthquakes like this one, now known to be particularly dangerous for generating tsunamis, are called tsunamogenic earthquakes. The height of the Nicaraguan tsunami was about 10 times greater than predicted for an earthquake of this magnitude.

The tsunami that was generated by the slow Nicaraguan earthquake of 1992 was up to 40 feet (12 m) high at nearby beachfronts, and it swept homes, vehicles, and unsuspecting people to sea within 40 minutes of the earthquake. The tsunami had a relatively slow run-up velocity, so that many people were able to outrun the wave, but elderly, sick, sleeping, and sedentary people and young children could not escape. The beachfront was heavily damaged, and 170 people were drowned by the tsunami. After the initial disaster, the hazards were not over, because the tsunami had ripped through water storage and sewage treatment plants, and the resulting contamination caused an outbreak of cholera that took even more lives in the following weeks.

1964 Alaska Earthquake-related Tsunami

Southern Alaska is hit by a significant tsunami every 10 to 30 years. The earthquakes are generated along the convergent plate boundary where oceanic crust of the Pacific plate is being pushed back into the mantle beneath Alaska. Continental crust of the North American plate in Alaska is moving over the Pacific plate, along a huge fault zone known as the Aleutian-Alaska megathrust zone, which is part of the subduction zone between the Pacific and North American plates. This fault dips at only 20° north, so motion on the fault causes large displacements of the seafloor, and hence generates large tsunamis. This fault zone has generated large Pacific Ocean tsunamis in 1878, 1946, 1957, and 1964, with many smaller events in between these major events. During the magnitude 9.2 March 27, 1964, earthquake in Alaska, approximately 35,000 square miles (90,650 km^2) of seafloor and adjacent land were suddenly thrust upward by up to 35 feet (11.5 m), as part of more regional movements of the land during this event. About 83,000 square miles (215,000 km^2) of seafloor was displaced significantly upward, while other areas of southern Alaska moved downward. This mass movement generated a huge tsunami as well as many related seiche-like waves in surrounding bays. The tsunami generated from this earthquake caused widespread destruction in Alaska, especially in Seward, Valdez, and Whittier. These towns all experienced large earthquake-induced submarine landslides, some of which tore away parts of the towns' waterfronts. The submarine landslides also generated large tsunamis that cascaded over these towns barely after the ground stopped shaking from the earthquake.

The earthquake that struck southern Alaska at 5:36 P.M. on Friday, March 27, 1964, was one of the largest earthquakes ever recorded, second in the amount of energy released only to the 1960 Chile earthquake, and followed closely by the 2004 Sumatra magnitude 9.0 earthquake. The epicenter was located in northern Prince William Sound, and the focus, or point of initial rupture, was located at a remarkably shallow 14 miles (23 km) beneath the surface. The energy released during the Valdez earthquake was more than the world's largest nuclear explosion, and greater than the Earth's total average annual release of seismic energy; yet, remarkably, only 131 people died during this event. Damage is estimated at 240 million dollars (1964 dollars), a surprisingly small figure for an earthquake this size. During the initial shock and several other shocks that followed in the next one to two minutes, a 600-mile- (1,000-km-) long by 250-mile- (400-km-) wide slab of subducting oceanic crust slipped further beneath the North American crust of southern Alaska. Ground displacements above the area that slipped were tremendous—much of the Prince William Sound and Kenai Peninsula area moved horizontally almost 65 feet (20 m) and moved upward by more than 35 feet (11.5 m). Other areas more landward of the uplifted zone were down dropped by several to 10 feet (3 m). Overall, almost 200,000 square miles (520,000 km^2) of land saw significant movements upward, downward, and laterally during this huge earthquake. These movements suddenly displaced an estimated volume of water of 6,000 cubic miles (25,000 km^3).

The ground shook in most places for three to four minutes during the March 27, 1964, earthquake, but lasted for as much as seven minutes in a few places such as Anchorage and Valdez, where unconsolidated sediment and fill amplified and prolonged the shaking. The shaking caused widespread destruction in southern Alaska and damage as far away as southern California and induced noticeable effects across the planet. Entire neighborhoods and towns slipped into the sea during this earthquake, and ground breaks, landslides, and slumps were reported across the entire region. The Hanning Bay fault on Montague Island, near the epicenter, broke through the surface, forming a spectacular fault scarp with a displacement of more than 15 feet (3 m), uplifting beach terraces and mussel beds above the high-water mark, many parts of which rapidly eroded to a more stable configuration. Urban areas such as Anchorage suffered numerous landslides and slumps, with tremendous damage done by translational slumps where huge blocks of soils and rocks slid on curved faults downslope, in many cases toward the sea. Houses ended up in neighbors' backyards, and some homes were split in two by ground breaks. A neighborhood in Anchorage known as Turnagain Heights suffered extensive damage when huge sections of the underlying ground slid toward the sea on a weak layer in the bedrock known as the Bootlegger Shale, which lost cohesion during the earthquake shaking.

The transportation system in Alaska was severely disrupted by the earthquake. All major highways and most secondary roads suffered damage to varying degrees—186 of 830 miles (300 of 1,340 km) of roads were damaged, and 83 miles (125 km) of roadway needed replacement. Seventy-five percent of all bridges collapsed, became unusable, or suffered severe damage. Many railroad tracks were severed or bent by movement on faults, sliding and slumping into streams, and other ground motions. In Seward, Valdez, Kodiak, and other coastal communities, a series of three to 10 tsunami waves tore trains from their tracks, throwing them explosively onto higher ground. The shipping industry was devastated, which was especially difficult as Alaskans use shipping for more than 90 percent of their transportation needs, and the main industry in the state is fishing. Submarine slides, tsunamis, tectonic uplift and subsidence, and earthquake-induced fires totally destroyed all port facilities in southern Alaska except those in Anchorage. Huge portions of the waterfront facilities at Seward and Valdez slid under the sea during a series of submarine landslides, resulting in the loss of the harbor facilities and necessitating the eventual moving of the cities to higher, more stable ground. Being thrown to higher ground by tsunamis destroyed hundreds of boats, although no large vessels were lost. Uplift in many shipping channels formed new hazards and obstacles that had to be mapped to avoid grounding and puncturing hulls. Downed lines disrupted communication systems, and initial communications with remote communities were taken over by small, independently powered radio operators. Water, sewer, and petroleum storage tanks and gas lines were broken, exploded, and generally disrupted by slumping, landslides, and ground movements. Residents were forced to obtain water and fuel trucked in to areas for many months while supply lines were restored. Groundwater levels generally dropped, in some cases below well levels, further compounding the problems of access to freshwater.

Most damage from the 1964 Alaskan earthquake was associated with the numerous tsunamis and seiche waves generated during this event. A major Pacific-wide tsunami was generated by the large movements of the seafloor and continental shelf, whereas other tsunamis were generated by displacements of the seafloor near Montague Island in Prince William Sound, by landslides, and by natural resonance in the many bays and fjords of southern Alaska.

The town of Seward on the Kenai Peninsula experienced strong ground shaking for about four minutes during the earthquake, and this initiated a series of particularly large submarine landslides and seichelike waves that removed much of the waterfront docks, train-yards, and streets. During the earthquake, a large section of the waterfront at Seward, several hundred feet (100 m) wide and more than half a mile long (1 km), slid into the ocean along a curved fault surface. The movement of such significant quantities of material underwater generated a tsunami with a 30-foot (9-m) run-up that washed over Seward about 20 minutes after the earthquake. The earthquake and landslides tore apart many seafront oil storage facilities, and the oil caught fire and exploded, sending flames 200 feet (60 m) into the air. The oil on the waves caught fire, and rolled inland on the 30–40-foot- (9–12 m-) high tsunami crests. These flaming waves crashed into a train loaded with oil, causing each of 40 successive tankers to explode one after the other as the train was torn from the tracks. The waves moved inland, carrying boats, train cars, houses, and other debris, much of it in flames. The mixture moved overland at 50–60 miles per hour (80–100 km/hr), raced up the airport runway, and blocked the narrow valley marking the exit from the town into the mountains. The tsunami had several large crests, with many reports of the third being the largest. Twelve people died in Seward, and the town was declared a total loss after the earthquake and ensuing tsunami. Seward was then moved to a new location a few miles away, on ground thought to be more stable from submarine landslides. Steep mountains mark the southwest side of the current town.

As the tsunami reached into the many bays and fjords in southern Alaska, it caused the water in many of these bays to oscillate back and forth in series of standing waves that caused widespread and repeated destruction. In Whittier, wave run-ups were reported to be up to 107 feet (32 m), and the town suffered submarine landslides, which destroyed oil and train facilities. Submarine landslides, seichelike waves, 23-foot- (7-m-) high tsunamis, and exploding oil tanks similarly affected Valdez. Near Valdez, the tsunami broke large trees, leaving only stumps more than 100 feet (30 meters) above high-tide mark. The tsunami deposited driftwood, sand, and other debris up to 170 feet (67 m) above sea level near Valdez. Like Seward, Valdez was built on a glacial outwash delta at the head of the fjord, and large sections of the delta collapsed and slid under the sea during the earthquake. A section of the town 600 feet (180 m) wide and nearly a mile (1.3 km) long slipped beneath the waters of the fjord during the earthquake, followed within minutes by a 30-foot- (9-m-) high tsunami that swept into town, killing 32 people. The natural resonance of the bay at Valdez caused the water to oscillate for hours, such that five to six hours after the initial tsunami, another series of waves grew, and continued to wash into the town with crests moving through the town near midnight on March 27; then another tsunami crest hit at 1:45 the following afternoon, moving through downtown as a tidal bore.

The town of Kodiak, 500 miles (800 km) from the epicenter, also experienced extensive damage, and 18 people were killed. The land at Kodiak subsided 5.6 feet (1.7 m) during the earthquake, and then the town was hit by a series of at least 10 tsunami crests up to 20 feet (6 m) high that destroyed the port and dock facilities as well as more than 200 other buildings.

Within 25 minutes of the earthquake, the huge displacements of water had organized into a deep-water tsunami that was moving southward into the open Pacific Ocean. This wave had a period of more than an hour, and in many places the first wave to hit was characterized by a slow rise of water into coastal areas, but the second wave was more powerful and associated with a steep breaking wave. When the tsunami reached the state of Washington four hours after the earthquake, it washed up in most places as a five-foot- (1.5 m-) tall wall of water, and was decreased in amplitude to two feet by the time it got to Astoria, Oregon. Local bays and other effects caused some variations, and the maximum wave heights in all of Washington, Oregon, and California generally were in the range of 14–15 feet (4.3–4.5 m). However, when the wave got to Crescent City, California, the shapes of the seafloor and bay were able to focus the energy from this wave into a series of five tsunami crests. The fourth was a 21-foot- (6.3-m-) high crest that swept into downtown, washing away much of the waterfront district and killing 11 people, after they had returned to assess the damage from the earlier wave crests. This fourth wave was preceded by a large withdrawal of water from the bay, such that boats were resting on the seafloor. When the large crest of the fourth wave hit the city, it washed inland through 30 city blocks and destroyed waterfront piers and docks. Later analysis of the Crescent City area has shown that the bay has been hit by at least 13 significant historical tsunamis, and the shape of the seafloor serves to amplify waves that enter the bay.

Other locations along the California coast were luckier than Crescent City but still suffered destruction of piers, boats, and other waterfront facilities. One potential disaster was averted, perhaps fortuitously, in San Francisco. About 10,000 people had rushed to the waterfront to watch the tsunami as it was supposed to pass the city. These people did not know the dangers, but the shape of the seafloor and bays in this region did not amplify the waves as occurred in Crescent City, so no lives were lost. The tsunami continued to move around the Pacific, being recorded as 7.5-foot (2.3-m) waves in Hawaii and smaller crests across Japan, South America, and Antarctica.

1946 Hilo, Hawaii, Tsunami

On April 1, 1946, an earthquake generated near the Unimak Islands in Alaska devastated vast regions of the Pacific Ocean. This tsunami was one of the largest and most widespread tsunamis to spread across the Pacific Ocean this century.

A lighthouse at Scotch Cap in the Aleutians was the first to feel the effect of the tsunami. At about 1:30 P.M., the crew of five at the lighthouse recorded feeling an earthquake lasting 30–40 seconds, but no serious damage occurred. A second quake was felt nearly half an hour later, also with no damage. Fifty minutes after the earthquake, the crew of a nearby ship recorded a "terrific roaring of the sea, followed by huge seas." They reported a wave (tsunami) that rose over the top of the Scotch Cap lighthouse and over the cliffs behind the station, totally destroying the lighthouse and coast guard station. The lighthouse was built of steel-reinforced concrete and sat on a bluff 46 feet (14 m) above sea level. The wave is estimated to have been 90–100 feet (27–30 m) high. A rescue crew sent to Scotch Cap lighthouse five hours after the disaster reported that the station was gone, and debris (including human organs) was strewn all over the place. There were no survivors.

Many hours later, the tsunami had traveled halfway across the Pacific and was encroaching on Hawaii. Residents of Hilo, Hawaii, first noticed that Hilo Bay drained, and springs of water sprouted from the dry seafloor that was littered with dying fish. As the residents wondered at the cause of the water's suddenly draining from their bay, a series of huge waves came crashing in from the ocean and quickly moved into the downtown district. Buildings were ripped from their foundations and thrown into adjacent structures, bridges were pushed hundreds of feet (hundreds of meters) upstream from their crossings, and boats and railroad cars were tossed about like toys. After the tsunami receded, Hilo was devastated, with a third of the city destroyed and 96 people dead. Outside Hilo, entire villages disappeared and were washed into the sea along with their residents.

1896 Kamaishi (Sanriku) Tsunami

On June 15, 1896, 27,000 people died in a huge tsunami that swept over the seaport of Kamaishi, Japan. A local earthquake caused mild shaking of the port city, which was not unusual in this tectonically active area. However, 20 minutes later the bay began to recede, then 45 minutes after the earthquake, the port city was inundated with a 90-foot- (27-m-) high wall of water that came in with a tremendous roar. The town was almost completely obliterated, and 27,000 people, mostly women and children, perished in a few short moments. Kamaishi was a fishing port, and when the tsunami struck, the fishing fleet was at sea and did not notice the tsunami, since it had a small amplitude in the deep ocean. When the fishing fleet returned the next morning, they sailed through many miles of debris, thousands of bodies, and reached their homes only to find a few smoldering fires among a totally devastated community.

1960 Chile Earthquake and Tsunami

The great magnitude 9.5 Chilean earthquake of May 22, 1960, generated a huge tsunami that killed more than 1,000 people near the earthquake epicenter and almost 1,000 more as the wave propagated across the Pacific Ocean. This tsunami was generated along the convergent boundary between the small Nazca oceanic plate in the Pacific Ocean and southern South America. This part of the "Ring of Fire" convergent boundary generates more tsunamogenic earthquakes than anywhere else on the planet, unleashing a large tsunami about every 30 years. Damage from the

1960 earthquake led directly to the establishment of the modern Pacific tsunami warning system.

Saturday, May 21, began as a normal day in Chile, a morning soon interrupted by a series of about 50 significant earthquakes that shook the continent beginning at 6:02 A.M. The first tremor destroyed much of the area around Concepción, with a sequence of aftershocks that continued until 3:11 P.M. the following day. Then, on May 22, there were two massive earthquakes with magnitudes of 8.9 and 9.5, with their hypocenters located a mere 20 miles (33 km) below the surface. A section of the seafloor and coast nearly 200 miles (300 km) long experienced sudden uplift of 3.3 feet (1 m), and subsidence of the land of 5 feet (1.6 m) occurred across an area of 5,000 square miles (13,000 km^2), extending 18 miles (29 km) inland.

Since the area was (and still is) prone to tsunamis generated from earthquakes, local coastal fishermen knew that such a large earthquake would likely be followed by a giant tsunami, so they rapidly took their families and ran their boats to the open ocean. This knowledge of how to respond to tsunamis undoubtedly saved many lives initially, since 10 to 15 minutes after the large quake, a 16-foot- (5-m-) high tsunami rolled into many shoreline areas, causing destruction of dock areas and coastal villages. However, after this wave washed back to sea, many fishermen returned, or stayed close to shore. This was a mistake, since 50 minutes after the first wave retreated, another, larger crest struck, this time as a 26-foot- (8-m-) tall wall of water that crashed into the shore at a remarkable speed of 125 miles per hour (200 km/hr). Many of the deaths in Chile were reportedly related to the fact that after the first tsunami crest passed, many Chileans assumed the danger was over and returned to the shoreline. The second crest had a run-up of 26 feet (7.8 m) and was followed by a third crest with a height of 36 feet (11 m) that moved inland at about half the speed of the second wave, but was so massive that it inflicted considerable damage. For the next several hours the coast was pounded by a series of waves that virtually destroyed most of the development along the coastline between Concepción and Isla Chiloe. Run-up heights were variable along the coast in the southern part of Chile, with most between 28 and 82 feet (8.5 and 25 m). The number of people that were killed in Chile by this tsunami is unknown because of poor documentation, but most estimates place it between 5,000 and 10,000 people.

The massive earthquakes of May 22 sent a series of tsunami crests racing across the Pacific Ocean at 415–460 miles per hour (670–740 km/hr) and around the world for the next 24 or more hours. The tsunami train had wavelengths of 300–500 miles (500–800 km), periods of 40–80 minutes between passing crests, and was only a little more than a foot high (40 cm) in the open ocean. The waves swept up the coast of South America, then the western United States, where run-up heights were small, typically less than 4 feet (1.2 m), but locally up to 12 feet. The tsunami was accurately predicted to hit Hawaii 14.8 hours after the earthquake, and it arrived within a minute of the predicted time. This should have saved lives, but 61 people were killed by this tsunami in Hawaii, including many who heard the warnings but rushed to the coast to watch the waves strike.

The response of the population of Hilo to tsunami warnings in 1960 is a lesson in the need to understand the hazards of tsunamis to save lives. As the tsunami approached Hawaii, the wave crests refracted around to the north side of the islands and hit the city of Hilo particularly hard, because of the shape of the shoreline features in Hilo Bay. Even though residents were warned of the danger, less than one-third of the population evacuated the coastal area when the warnings were issued, and about half remained after the first crest hit Hilo. Like many tsunamis, the first crests to invade Hilo were not the largest, and sightseers were surprised, and many killed, when the third crest pounded the downtown harbor and business district with a 20-foot (6-m) wall of water that carried 20-ton projectiles of pieces of the city wharf and waterfront buildings. The city suffered an inundation of 5 city blocks as the run-up reached 35 feet (10.7 m). Amazingly, about 15 percent of the city population stayed even through the largest waves. More than 540 homes and businesses were destroyed with tens of millions of dollars of damage (24 million 1960 dollars), and 61 residents of Hilo were dead.

Islands in the Western Pacific were widely affected, with the height of the waves largely determined by factors such as the shape of the shoreline, slope of the seafloor, and orientation of the beach with respect to the source in Peru. Pitcairn Island was the strongest hit, with run-up heights of more than 40 feet (12.2 m) reported. The effects of wave refraction around some Pacific islands focused some of the tsunami energy on Japan, where the run-up heights exceeded 20 feet (6.4 m). The combined effects of this refraction of wave energy from the distant earthquake, and natural resonance effects of some harbors that further amplified the waves, made the 1960 earthquake an unexpectedly large and devastating disaster in Japan. Approximately 22 hours after the earthquake the coast of Japan began to feel its destruction. The resonance effects caused the largest waves to grow hours after the initial wave crests hit Japan, whose east coast saw an average run-up of 9 feet (2.7 m). The resonance effects and seiching in the harbors caused the greatest damage, with 5,000 homes destroyed in Hokkaido and Honshu, 191 people killed and another 854 injured, and 50,000 left homeless. Property damage in Japan was estimated to exceed 400 million (1960) dollars.

VOLCANIC ERUPTION-INDUCED TSUNAMI

Some of history's most devastating tsunamis have been generated by volcanic processes, either during eruptions and landslides from the slopes of volcanoes or during collapse of the volcanic edifice into a caldera complex. Two of the most severe tsunamis from volcanic processes were from the 1815 eruption of Tambora, and from the 1883 eruption of Krakatau, both in Indonesia.

Tambora, Indonesia, 1815

The largest volcanic eruption ever recorded is that of the Indonesian island arc volcano Tambora in 1815. This eruption initially killed an estimated 92,000 people, largely from the associated tsunami. The eruption sent so much particulate matter into the atmosphere that it influenced the climate of the planet, cooling the surface and changing patterns of rainfall globally. The year after the eruption is known as "the year without a summer" in reference to the global cooling caused by the eruption, although people at the time did not know the reason for the cooling. In cooler climates, the year without a summer saw snow throughout the summer and crops were not able to grow. In response, great masses of farmers moved from New England in the United States to the Midwest and Central Plains, seeking a better climate for growing crops.

Tambora is located in the Indonesian region, a chain of thousands of islands that stretch from Southeast Asia to Australia. The tectonic origins of these islands are complex and varied, but many of the islands along the southwest part of the chain are volcanic in origin, formed above the Sumatra-Sunda trench system. This trench marks the edge of subduction of the Indian-Australia plate beneath the Philippine-Eurasian plates, which formed a chain of convergent margin island arc volcanoes above the subduction zone. Tambora is one of these volcanoes, located on the island of Sumbawa, east of Java. Tambora is unusual among the volcanoes of the Indonesian chain, as it is located further from the trench (210 miles; 340 km) and further above the subduction zone (110 miles; 175 km) than other volcanoes in the chain. This is related to the fact that Tambora is located at the junction of subducting continental crust from the Australian plate and subducting oceanic crust from the Indian plate. A major fault cutting across the convergent boundary is related to this transition, and the magmas that feed Tambora seem to have risen along fractures along this fault.

Tambora has a history of volcanic eruptions extending back at least 50,000 years. The age difference between successive volcanic layers is large, and there appear to have been as much as 5,000 years between individual large eruptions. This comparatively large time interval may be related to Tambora's unusual tectonic setting far from the trench along a fault zone whose origin is related to differences between the types of material being subducted on either side of the fault.

In 1812 Tambora started reawakening with a series of earthquakes plus small steam and ash eruptions. People of the region did not pay much attention to these warnings, having not remembered the ancient eruptions of 5,000 years past. On April 5, 1815, Tambora erupted with an explosion that was heard 800 miles (1,300 km) away in Jakarta. Ash probably reached more than 15 miles (25 km) in the atmosphere but this was only the beginning of what was to be one of history's greatest eruptions. Five days after the initial blast a series of huge explosions rocked the island, sending ash and pumice 25 miles (40 km) into the atmosphere and sending hot pyroclastic flows (nuée ardentes) tumbling down the flanks of the volcano and into the sea, generating tsunamis. When the hot flows entered the cold water, steam eruptions sent additional material into the atmosphere, creating a scene of massive explosive volcanism and wreaking havoc on the surrounding land and marine ecosystems. More than 36 cubic miles (150 km^3) were erupted during these explosions from Tambora, more than 100 times the volume of the Mount St. Helens eruption of 1980.

Ash and other volcanic particles such as pumice from the April eruptions of Tambora coved huge areas that stretched many hundreds of miles across Indonesia. Towns located within a few tens of miles experienced strong, hurricane-force winds that carried rock fragments and ash, burying much in their path and causing widespread death and destruction. The ash caused a darkness like night that lasted for days even in locations 40 miles (65 km) from the eruption center, so dense was the ash. Roofs collapsed from the weight of the ash, and 15-foot-(4.5-m-) tall tsunamis were formed when the pyroclastic flows entered the sea. These tsunamis swept far inland in low-lying areas, killing and sweeping away many people and livestock. A solid layer of ash, lumber, and bodies formed on the sea extending several miles west from the island of Sumbawa, and pieces of this floating mass drifted off across the Java sea. Although it is difficult to estimate, at least 92,000 people were killed in this eruption. Crops were incinerated or poisoned and irrigation systems destroyed, resulting in additional famine and disease after the eruption ceased, killing tens of thousands of people that survived the initial eruption, and forcing hundreds of thousands of people to migrate to neighboring islands.

The year of 1816 is known as the year without a summer, caused by the atmospheric cooling from the sulfur dioxide released from Tambora. Snow fell in many areas across Europe and in some places was colored yellow and red from the volcanic particles in the atmosphere. Crops failed, people suffered, and social and economic unrest resulted from the poor weather, and the Napoleonic wars soon erupted. Famine swept Europe hitting France especially hard, with food and antitax riots erupting in many places. The number of deaths from the famine in Europe is estimated at another 100,000 people.

Krakatau, Indonesia, 1883

Indonesia has seen catastrophic volcanic eruptions and associated tsunamis other than from Tambora. The island nation of Indonesia has more volcanoes than any other country in the world, with more than 130 known active volcanoes. These volcanoes have been responsible for about one-third of all the deaths attributed to volcanic eruptions and associated tsunamis in the world. Indonesia stretches for more than 3,000 miles (5,000 km) between Southeast Asia and Australia, is characterized by very fertile soils and a warm climate, and is one of the most densely populated places on Earth. The main islands in Indonesia include, from Northwest to Southeast, Sumatra, Java, Kalimantan (formerly Borneo), Sulawesi (formerly Celebes), and the Sunda Islands. The country averages one volcanic eruption per month and because of the dense population, Indonesia suffers from approximately one-third of the world's fatalities from volcanic eruptions and associated phenomena such as tsunamis.

One of the most spectacular and devastating eruptions of all time was that of 1883 from Krakatau, an uninhabited island in the Sunda Strait off the coast of the islands of Java and Sumatra. This eruption generated a sonic blast that was heard thousands of miles away, spewed enormous quantities of ash into the atmosphere, and initiated a huge tsunami that killed roughly 40,000 people and wiped out more than 160 towns. The main eruption lasted for three days, and the huge amounts of ash ejected into the atmosphere circled the globe, remaining in the atmosphere for more than three years, forming spectacular sunsets, and affecting global climate. Locally, the ash covered nearby islands, killing crops, natural jungle vegetation, and wildlife, but most natural species returned within a few years.

Legends in the Indonesian islands discuss several huge eruptions from the Sunda Strait area, and geological investigations confirm many deposits and calderas from ancient events, and recent work has revealed the presence of ancient tsunami deposits around the straits. Prior to the 1883 eruption, Krakatau consisted of several different islands including Perbuwatan in the north, Danan, and Rakata in the south. The 1883 eruption emptied a large underground magma chamber, resulting in the formation of a large caldera complex. During the 1883 eruption, Perbuwatan, Danan, and half of Rakata collapsed into the caldera and sank below sea level. Since then a resurgent dome has grown out of the caldera, emerging above sea level as a new island in 1927. The new island is named Anak Krakatau (child of Krakatau), growing to repeat the cycle of cataclysmic eruptions in the Sunda Strait.

Prior to the 1883 eruption, the Sunda Strait was densely populated with many small villages built from bamboo and palm-thatched roofs and other local materials. Krakatau is located in the middle of the strait, with many starfish-shaped arms of the strait extending into the islands of Sumatra and Java. Many villages, such as Telok Betong, lay at the ends of these progressively narrowing bays, pointed directly at Krakatau. These villages were popular stops for trading ships from the Indian Ocean to stop and obtain supplies before heading through the Sunda Strait to the East Indies. The group of islands centered on Krakatau in the center of the strait was a familiar landmark for these sailors.

Although not widely appreciated as such at the time, the first signs that Krakatau was not a dormant volcano but was about to become very active appeared in 1860 and 1861 with small eruptions, then a series of earthquakes between 1877 and 1880. On May 20, 1883, Krakatau entered a violent eruption phase, witnessed by ships sailing through the Sunda Strait. The initial eruption sent a seven-mile-(11-km-) high plume above the strait, with the eruptions heard 100 miles (160 km) away in Jakarta. As the eruption expanded, ash covered villages in a 40-mile (60 km) radius. For several months the volcano continued to sporadically erupt covering the straits and surrounding villages with ash and pumice, while the earthquakes continued.

On August 26, the style of the eruptions took a severe turn for the worse. A series of extremely explosive eruptions sent an ash column 15 miles (25 km) into the atmosphere, sending many pyroclastic flows and nuées ardentes spilling down the island's slopes and into the sea. Tsunamis associated with the flows and earthquakes sent waves into the coastal areas surrounding the Sunda Strait, destroying or damaging many villages on Sumatra and Java. Ships passing through the straits were covered with ash, while others were washed ashore and shipwrecked by the many and increasingly large tsunamis.

On August 27, Krakatau put on its final show, exploding with a massive eruption that pulverized the island and sent a large towering Plinian eruption column 25 miles (40 km) into the atmosphere. The blasts from the eruption were heard as far away as Australia, the Philippines, and Sri Lanka. Atmospheric pressure waves broke windows on surrounding islands and traveled around the world as many as seven times, reaching the antipode (area on the exactly opposite side of the Earth from the eruption) at Bogotá, Columbia, 19 hours after the eruption. The amount of lava and debris erupted is estimated at 18–20 cubic miles (75–80 km^3), making this one of the largest eruptions known in the past several centuries. Many sections of the volcano collapsed into the sea, forming steep-walled escarpments cutting through the volcanic core, some of which are preserved to this day. These massive landslides were related to the collapse of the caldera beneath Krakatau and contributed to huge tsunamis that ravaged the shores of the Sunda Strait, with average heights of 50 feet (15 m), but reaching up to 140 feet (40 m) where the V-shaped bays amplified wave height. Many of the small villages were swept away with no trace, boats were swept miles inland or ripped from their moorings, and thousands of residents in isolated villages in the Sunda Strait perished.

The tsunami was so powerful that many trees were ripped from the soil, leaving only shattered stumps remaining as vestiges of the previous forest. In some places the forest was uprooted to elevations of 130 feet (40 m) above sea level. Bodies were strewn around the shores of the Sunda Strait and formed horrible scenes of death and destruction that survivors were not equipped to clean up. The population was decimated, food supplies and farm land were destroyed, and entire villages and roads were wiped off the islands or buried in deep layers of mud. Survivors were in a state of shock and despair after the disaster and soon had to deal with more loss when disease and famine took additional lives. Soon a state of anarchy took over as rural people and farmers from the mountains descended to the coastal region and engaged in ganglike tribal looting and robbery, creating a state of chaos. Within a few months, however, troops sent by the colonial Dutch government regained control and began the rebuilding the region. Nevertheless, many of the coastal crop lands had their soil horizons removed and were not arable for many decades to come. Coastal reefs that served as fishing grounds were also destroyed, so without fishing or farming resources, many of the surviving residents moved from the coast into interior regions.

Although it is uncertain how many people died in the volcanic eruption and associated tsunamis, the Dutch colonial government estimated in 1883 that 36,417 people died, most of them (perhaps 90 percent) from the tsunamis. Several thousand people were also killed by extremely powerful nuées ardentes, or glowing clouds of hot ash, that raced across the Sunda Strait on cushions of hot air and steam. These clouds burned and suffocated all who were unfortunate enough to be in their direct paths.

Tsunamis from the eruption spread out across the Indian Ocean, caused destruction across many of the coastal regions of the entire Indian Ocean, and spread around the world. Although documentation of this Indonesian tsunami is not nearly as good as that from the 2004 tsunami, many reports of the tsunami generated from Krakatau document this event. Residents of coastal India reported the sea suddenly receding to unprecedented levels, stranding fish that were quickly picked up by residents, many of whom were then washed away by large waves. The waves spread into the Atlantic Ocean and were detected in France, and a seven-foot- (2-m-) high tsunami beached fishing vessels in Auckland, New Zealand.

Weeks after the eruption, huge floating piles of debris and bodies were still floating in the Sunda Strait, Java Strait, and Indian Ocean, providing grim reminders of the disaster to sailors in the area. Some areas were so densely packed with debris that sailors reported they appeared to be solid ground, and people were able to walk across the surface. Fields of pumice from Krakatau reportedly washed up on the shores of Africa a year after the eruption, some even mixed with human skeletal remains. Other pumice rafts carried live plant seeds and species to distant shores, introducing exotic species across oceans that normally acted as barriers to plant migration.

On western Java, one of the most densely populated regions in the world, destruction on the Ujong Kulon Peninsula was so intense that the peninsula was designated a national park, as a reminder of the power and continued potential for destruction from Krakatau. Such designation of hazardous coastal and other areas of potential destruction as national parks and monuments is good practice for decreasing the severity of future natural eruptions and processes.

Krakatau began rebuilding new cinder cones that emerged from beneath the waves in 1927 through 1929, when the new island, named Anak Krakatau (child of Krakatau) went into a rapid growth phase. Several cinder cones have now risen to heights approaching 600 feet (190 m) above sea level. The cinder cones will undoubtedly continue to grow until Krakatau's next catastrophic caldera collapse eruption.

LANDSLIDE-INDUCED TSUNAMIS

Many tsunamis are initiated by landslides that displace large amounts of water. These include rockfalls and avalanches, such as the huge avalanche that triggered a 200-foot- (60-m-) high tsunami in Lituya Bay, Alaska. Submarine landslides tend to be larger than avalanches that originate above the water line, and they have generated some of the largest tsunamis on records. Many submarine landslides are earthquake-induced, whereas others are triggered by storm events and by increases in pressure on the sediments on the continental shelf induced by rises in sea level.

The 1958 Lituya Bay, Alaska, Tsunami

One of the largest-known landslide-induced tsunamis struck Lituya Bay of southeastern Alaska on July 9, 1958. Lituya Bay is located about 150 miles (240 km) southeast of Juneau and is a steep-sided, seven-mile- (11-km-) long, glacially carved fjord with T-shaped arms at the head of the bay where the Lituya and Crillon Glaciers flow down to the sea. The glaciers are rapidly retreating, a rock spit known as La Chausse Spit blocks the entrance to the bay, and a large island, Cenotaph Island, rests in the center of the fjord. Forest-covered mountains rise 6,000 feet (1,800 m) out of the water. As the fjord is a glacially carved valley, it has a rounded floor under the sea, with a depth of only 720 feet (220 m). The rocks surrounding the bay are part of the Pacific plate, and the Fairweather fault, the boundary between the Pacific and North American Plates, lies just inboard of the bay.

At 10:15 P.M. on July 9, 1958, a magnitude 7.9–8.3 earthquake struck the region along the Fairweather fault 13 miles (20.8 km) Southeast of the bay. The ground surface was displaced by up to 3.5 feet (1.1 m) vertically and 20 feet (6.3 m) horizontally in Crillon and Lituya Bays. In some locations, ground accelerations in a horizontal direction exceeded twice the force of gravity and approached the force of gravity in the vertical direction. The earthquake sent a huge mass of rock plunging into the water below, released from about 3,000 feet (900 m) up the cliffs near the head of the bay next to Lituya Glacier. This material landed in the water at the head of Lituya Bay and created a huge semicircular crater 800 feet (250 m) across, circling the rockfall. The force of the impact of the rockfall was so great that it tore off the outer 1,300 feet (400 m) of Lituya Glacier and threw it high into the air (an observer at sea reported seeing the glacier rise above the surrounding ridges). The wave generated by this massive collapse was enormous. The first wave (really a splash) soared up to 1,720 feet (524 m) on the opposite side of the bay, removing trees and soil with the force of the wave and the backwash. This splash reached heights that were three times deeper than the water in the bay. It washed over Cenotaph Island in the middle of the bay, destroying a government research station and killing two geologists stationed there who happened to be investigating the possibilities of tsunami hazards in the bay. A 100–170-foot- (30–51-m-) high tsunami was generated that moved at 96–130 miles per hour (155–210 km/hr) out toward the mouth of the bay, erasing shoreline features along its path and shooting a fishing troller out of the bay into open water.

The size of the tsunami produced by this landslide was exceptional, being eight times higher than the next highest known landslide- or rockfall-induced tsunami from a Norwegian fjord. Most landslides that fall into the water do not produce large tsunamis because only about 4 percent of the energy from the rockfall is transferred to the water to form waves in these events. Therefore, some geologists have suggested that the Lituya Bay tsunami may have had help from an additional source, such as a huge surge of water from an ice-dammed lake on Lituya glacier that may have been suddenly released during the earthquake, and the rockfall may have landed on this huge surge of water. However, even if this speculative release of water occurred, it still would not be enough to create such a large wave. A better understanding of this wave generation phenomenon is needed and awaits further study.

Lituya Bay and others like it have experienced numerous tsunamis as shown by distinctive scour marks and debris deposits found in the bay. Studies have shown that tsunamis in the bay in 1853 and 1936 produced run-up heights of 400 and 500 feet (120 and 150 m) above sea level. This phenomenon was also well known to the native Tlingit, who had legends of spirits who lived in the bay who would send huge waves out to punish those who angered them.

Giant Landslide-induced Tsunamis in Hawaii

Many volcanic islands, such as those of the Hawaiian chain in the Pacific, Reunion in the Indian Ocean, and the Canary Islands and Tristan da Cunha in the Atlantic, are built through a combination of volcanic flows adding material to a small area in the center of the island. Frequent submarine landslides cause the islands to collapse, spreading the rocks from these flows across a wide area. Undersea mapping of the Hawaiian chain using sonar systems that can produce detailed views of the seafloor have shown that the island chain is completely surrounded by a series of debris fans and aprons from undersea landslides, covering a much larger area than the islands themselves. Submarine mapping efforts have discovered more than 70 giant landslide deposits along the 1,360-mile- (2,200-km-) long segment of the island chain from Hawaii to Midway Island. The age of the islands and flows increases from Hawaii to Midway, and studies have suggested that the average recurrence time between giant submarine slides along the Hawaiian chain is 350,000 years. The youngest giant slides on Hawaii, the Alika slides, are estimated to be several hundred thousand years old, suggesting that parts of the Hawaiian chain could be close to being ready to produce another giant slide.

Many of the landslides on the Hawaiian Islands are 100–200 miles (150–300 km) long, but seem to be somewhat shorter for the older volcanoes to the west. The largest ones have displaced volumes of material up to 1,200 cubic miles (5,000 km^3). Many started on the top of the volcano near where different rift zones meet at the flank of the volcano. Giant slides that start near the topographic highs of the islands carve out a semicircular amphitheater on the island, and repeated slides from different directions can carve out the island into the shape of a star. The starlike shape of many volcanic islands is therefore the result of repeated volcanism-landslide cycles, acting together to build a high and wide volcanic edifice.

Giant landslides on volcanic islands may be initiated by many causes. Most seem to be triggered by earthquakes or by the collapse of slopes of volcanoes that are inflated by magma and ready to erupt. However, in other cases the volcanoes have built up such steep and unstable slopes that relatively minor events have triggered the release of giant landslides. These events have included the stresses from storm surges, internal waves in the ocean at depth, or pronounced rainfall events.

When the slopes of the volcanoes collapse, they typically produce several different types of submarine slides simultaneously. The submarine slides may begin at the surface or underwater as slumps, where large volumes of material move outward and downward on curved fault surfaces, some of which extend to about six miles (10 km) depth. These slumps can carve out huge sections of the island, but usually move too slowly to produce tsunamis. However, this is not always the case, and the Hawaiian Islands are famous for having earthquakes generated by fast-moving slumps that in turn do produce tsunamis. For instance, in 1868 a magnitude 7.5 earthquake was generated by a slump that produced a 66-foot- (20-m-) high tsunami, killing 81 people. In 1975 a 3.5 magnitude quake occurred on Kilauea when a 37-mile- (60-km-) long section of the flank of the volcano slumped 25 feet (8 m) laterally and 12 feet downward (3.5 m), forming a 47-foot- (14.3-m-) high tsunami that killed 16 people on the shoreline. Similar slumps and earthquakes are frequent occurrences on the Hawaiian Islands, but only some produce tsunamis.

The most dangerous submarine slides are the giant and fast moving debris avalanches. These chaotic flows can start as slumps, then break into incoherent masses of moving debris that flow downslope at hundreds of miles (km) per hour. The large volumes and high speeds of these flows make them very potent tsunami generators. The largest known submarine debris flow around the Hawaiian Islands is the 200,000-year-old Nuuanu debris avalanche on the northern side of Oahu. This flow deposit is 150 miles (230 km) long, covers an area of 14,300 square miles (23,000 km^2) and is more than a mile (2 km) thick at its source, making it one of the largest debris avalanches known on Earth. The sheer volume of the material in this flow, which probably moved at hundreds of miles (km) per hour, would have sent huge tsunamis moving around the Pacific. Models suggest that this debris avalanche would have caused tsunami run-ups of more than 65 feet (20 m) along the west coast of the United States.

Some of the younger submarine slide deposits around Hawaii that are much smaller than the Nuuanu slide have produced wave run-ups of up to 1,000 feet (305 m) on nearby islands, showing how locally devastating these slide-generated tsunamis may become. On the southwest side of the main island of Hawaii, two moderate-size slides, the 900-square-mile Alika 1 slide and the 650-square-mile Alika 2 slide (2,300 and 1,700 km^2, respectively) released about 150 cubic miles (600 km^3) of rock from Mauna Loa, excavating steep-sided amphitheaters on the island and sending the debris shooting downslope to the Pacific seafloor. Nearby islands have uncharacteristically high beach deposits that are a couple of hundred thousand years old and are probably tsunami deposits related to these slides. For instance, on the islands of Oahu, Molokai, and Maui, tsunami-related beach deposits are found at elevations of 213–260 feet (65–80 m) above sea level. On Lanai, boulder ridges form dunelike features that were deposited at more than 1,000 feet (326 m) above sea level by a catastrophic tsunami from this event. A wave with a run-up height of 1,000 feet (305 m) would need to be at least 100 feet (30 m) tall when it crashed on the coast. Areas closer to the coast on Lanai and Kahoolawe were stripped of their cover and soil to heights of 300 feet (100 m), dumping this material near the shore where it was redeposited in tsunami beds from later waves in this series of crests. This wave was so powerful when it struck the little island of Lanai that it not only removed the soil cover, but cracked the bedrock to 30 feet (10 m) depth, removing huge pieces of fractured bedrock, and filled the fractures with tsunami debris.

Landslide-induced Tsunamis of the Canary Islands, Atlantic Ocean

The Canary Islands form a hot-spot chain of small rugged volcanic islands off the northwest coast of Africa. They constitute two provinces of Spain, Santa Cruz de Tenerife and Las Palmas. The highest point on the islands is Mt. Teide on Tenerife at 12,162 feet (3,709 m) above sea level, although the volcanoes actually rise more than 10,000–13,000 feet (3,000–4,000 m) from the seafloor before the rise above sea level. The Canary Islands are hot-spot type shield volcanoes, very similar to Hawaii, yet they have very steep and rugged topography with amphitheater-shaped cliffs rising out of the sea, forming steep-sided mountain horns where different amphitheaters intersect. The star shape of several of the islands, together with the amphitheater shapes of many of the bays, suggests that these islands, like the Hawaiian Islands, have been built by a combination of volcanic eruptions and construction of tall volcanic edifices that have in turn collapsed and spread through the action of large landslides that move the material further out to sea.

Mapping of the seafloor around the Canary Islands has revealed that they are surrounded by many debris avalanche deposits, giant landslide deposits, debris aprons, and far-reaching turbidites derived from the repeated collapse of the volcanic islands. A series of seven large debris flow and turbidite deposits all less than 650,000 years old are located on the west sides of the islands. Some of these include 35,000 cubic feet (1,000 m^3) of material that suddenly collapsed from the islands and was deposited at sea. On the Canary Islands, it is possible to trace landslide scars offshore into debris avalanche deposits that in turn grade into the far-traveled turbidite deposits. For instance, nearly 200 cubic miles (800 km^3) of material derived from a five-mile- (8-km-) long, 3,000-foot- (900-m-) high headwall scarp on El Hierro Island include huge boulders near shore, some up to three-quarters of a mile (1.2 km) across, grading in deeper water into a debris avalanche deposit that is up to 250 feet (75 m) thick. This debris flow covers about 580 square miles (1,500 km^2), then grades oceanward into a turbidite flow that extends 370 miles (600 km) to the northwest. This deposit is estimated to be 13,000–17,000 years old and undoubtedly initiated a tsunami. Tsunami deposits have been identified on some of the Canary Islands, most lying at heights up to 300 feet (90 m) above sea level (and one that is 650 feet, or 200 m high), but so far specific slides have not been correlated with specific historical tsunamis. Older deposits, such as a 133,000-year-old slide also from El Hierro, is thought to have generated a tsunami that devastated the Bahamas during the last interglacial period.

Tsunamis from Submarine Slides on Continental Margins of the Grand Banks of Newfoundland and Storegga, Norway

Submarine landslides on continental margins with steep slopes are known to have produced a number of destructive tsunamis. The causes of these slides are not always clear. Some seem to have been produced by small earthquakes, others by storms, some by rapid loading of thick and weak sedimentary layers by new sediments, and some may have been caused by the buildup and release of gas in the sedimentary sections. Several slides on passive continental margins and slopes have occurred soon after sea levels rose with the retreat of the glaciers, suggesting that the increased load of the additional water on oversteepened margins may play a role in slope failure and tsunami generation.

On November 18, 1929, a magnitude 7.2 earthquake initiated a large submarine slide from the southern edge of the Grand Banks of Newfoundland. The earthquake's epicenter was located 170 miles (280 km) south of Newfoundland, and the rupture occurred 12 miles (20 km) beneath the surface. The slide involved about 50 cubic miles (200 km^3) of material that slumped eastward, then mixed with more water and transformed into a giant turbidity current that traveled 600 miles (1,000 km) eastward at speeds of 35–60 miles per hour (60–100 km/h), as determined by the times at which a series of 12 submarine telegraph cables were snapped.

The submarine slide associated with the 1929 earthquake generated the most catastrophic tsunami known in Canadian history. The tsunami had run-up heights of 40 feet (13 m) along the south coast of Newfoundland, where the waves killed 27 people. The waves penetrated about half a mile (1 km) inland, and caused a total of about 400,000 (1929) dollars damage, including the damage to the submarine cables. The waves propagated down the east coast of North America, killing one person in Nova Scotia, and were observed as far as Charleston, South Carolina, and in Bermuda. The waves also crossed the Atlantic and were recorded in the Azores and along the coast of Portugal.

The Grand Banks tsunami is a very important event for understanding the present-day hazards of tsunamis along the Atlantic seaboard and in the Gulf of Mexico. The failure of the slope from an earthquake in a plate interior shows that significant risks exist anywhere there may be oversteepened thick piles of loosely consolidated sediments. Residents of coastal areas need to understand the threat from tsunamis and build structures accordingly.

The eastern coast of Norway has been the site of several large submarine landslides that have sent tsunamis raging across the Norwegian and North Seas, and into the open Atlantic. The largest of these are the Storegga slides, where masses of sediment slid from the shelf to deepwater at rates of 160 feet per second (50 m/sec), or 109 mph (175 km/hr) depositing material 250–1,500 feet (80–450 m) thick at the base of the slope and forming turbidite layers up to 65 feet (20 m) thick that traveled 300 miles (500 km) into the Norwegian Sea. The first well-documented slide occurred about 30,000 years ago, when about 930 cubic miles (3,880 km^3) of sediment suddenly slipped down the steep continental slope. At this time, sea levels were low because much of the world's ocean water was being used to make the continental glaciers that covered much of North America, Europe, and Asia. Therefore, the tsunami resulting from this slide did not affect the present-day coast line. However, two younger slides at Storegga, occurring between 8,000 and 6,000 years ago, struck during higher sea levels and left a strong imprint on the modern coastline. The later two slides were much smaller than the first, involving a total of 400 cubic miles (1,700 km^3) of sediment. The second slide has been dated to have happened 7,950 +/- 190 years ago and had a height in the open ocean at its source of 25–40 feet (8–12 m). The waves crashed into Iceland, Greenland, and Scotland within a couple of hours. Greenland and Iceland saw the maximum run-up heights of 30–50 feet (10–15 m), and the waves refracted into the North Sea, causing variable run-ups of 10–65 feet (3–20 m) feet on the north coast of Scotland. The wide range in run-up heights is due to the variable topography of the coast of Scotland and some uncertainty in the models to calculate run-up heights. These tsunamis scoured the coastline of Scotland and deposited tsunami sands and gravels 30–60 feet (10–20 m) above sea level in many places.

SUMMARY

One of the deadliest natural disasters in history unfolded on December 26, 2004, when a great undersea earthquake with a magnitude between 9.0–9.3 triggered a tsunami that devastated many coastal areas of the Indian Ocean, killing an estimated 283,000 people. The tsunami devastated large parts of coastal Indonesia such as Banda Aceh, then swept across islands in the Indian Ocean to strike Sri Lanka, India, and east Africa. The tsunami propagated into all of the world's oceans where it was locally amplified by local coastal effects, but generally did little damage outside the Indian Ocean. The Indian Ocean was not equipped with any tsunami warning system, so the wave successively surprised coastal residents and tourists visiting many beach resorts. If there had been even a simple warning system in place, then tens of thousands of lives may have been saved. Nations of the Indian Ocean have since invested in a tsunami warning system in order to prepare for future disasters.

Examination of historical tsunami events reveals that most are caused by large undersea earthquakes, since they displace vast amounts of water and can form waves that travel great distances before they dissipate. Undersea volcanic eruptions or collapse of calderas along the coast have also formed historical deadly tsunamis, with the most famous examples being the eruptions of Krakatau and Tambora in Indonesia. Volcanic-eruption-induced tsunamis can form large waves, but since they displace less water than earthquake-induced tsunamis, the waves dissipate faster than those from earthquakes. Giant landslides around volcanic islands and along continental margins have also generated large tsunamis in the historical and geological records.

See also BEACHES AND SHORELINES; EARTHQUAKES; GEOLOGICAL HAZARDS; PLATE TECTONICS; TSUNAMIS, GENERATION MECHANISMS.

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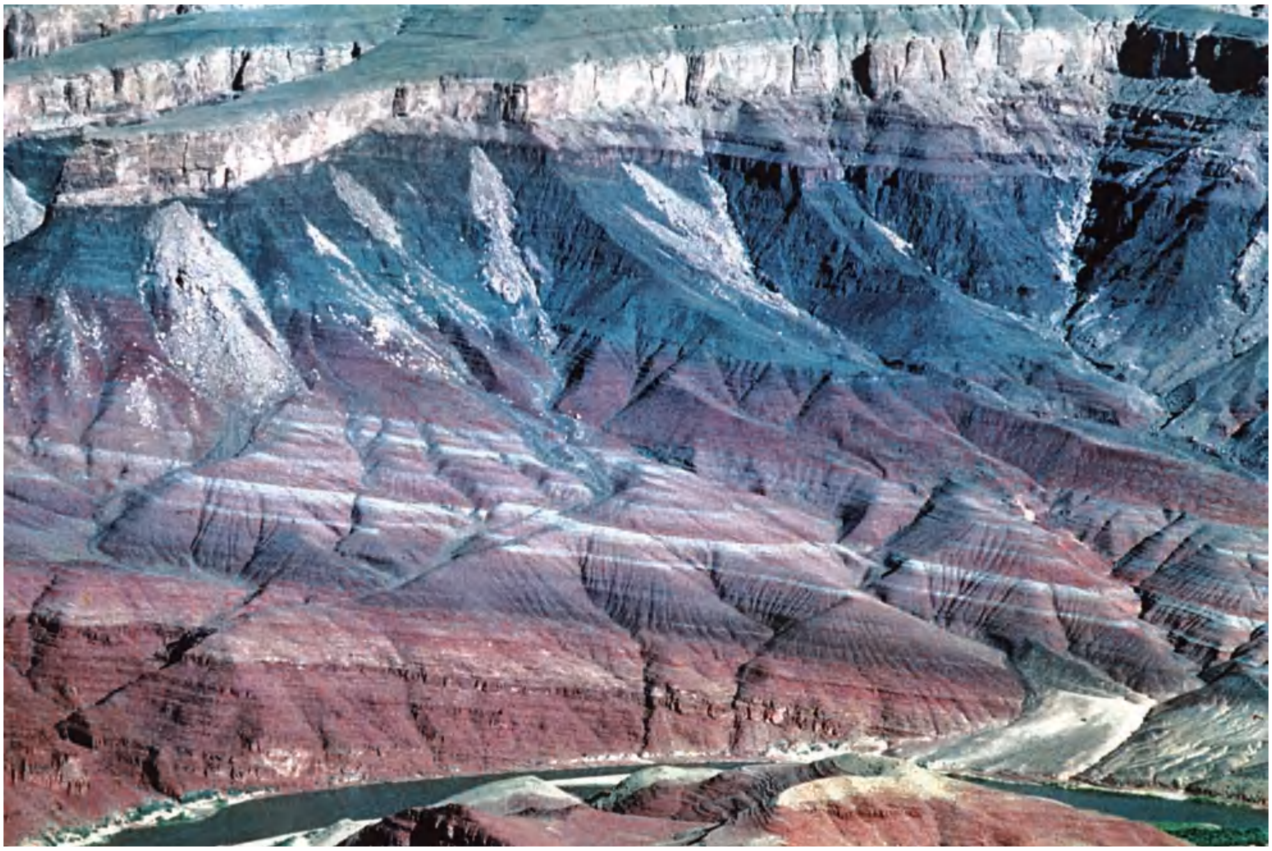
unconformities An unconformity is a substantial break or gap in a stratigraphic sequence that marks the absence of part of the rock record. These breaks may result from tectonic activity with uplift and erosion of the land, sea level changes, climate changes, or simple hiatuses in deposition. Unconformities normally imply that part of the stratigraphic sequence has been eroded but may also indicate that part of the sequence was not ever deposited in that location.



Angular unconformity, looking north from Moran Point, at Grand Canyon National Park, Arizona. Colorado River at bottom *(USGS)*

There are several different types of unconformities. Angular unconformities are angular discordances between older and younger rocks. Angular unconformities form in places where older layers were deformed and partly eroded before the younger layers were deposited. Disconformities represent a significant erosion interval between parallel strata. They are typically recognized by their irregular surfaces, missing strata, or large breaks between dated strata. Nonconformities are surfaces where strata overlie igneous or metamorphic rocks. Unconformities are significant in that they record an unusual event, such as tectonism, erosion, sea level change, or climate change.

Unconformities are typically overlain by a progradational marine sequence, starting with shallow water sandstone, conglomerate or quartzite, and succeeded by progressively deeper water deposits such as sandstone, shale, and limestone. Unconformities are often used by stratigraphers and other geologists to separate different packages of rocks deposited during different tectonic, climatic, or time systems.

See also HISTORICAL GEOLOGY; PLATE TECTONICS; STRATIGRAPHY, STRATIFICATION, CYCLOTHEM.

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universe The universe includes all matter and energy everywhere, including the Earth, solar system, galaxies, interstellar matter and space, regarded as a whole. The large-scale structure of the universe refers to mapping and characterization of the observable distributions of matter, light, and space, on scales of billions of light-years. Sky surveys from Earth and space-based observation platforms using a wide range of the electromagnetic spectrum have been used to determine what is presently known about the large scale structure of the universe and the types of matter and energy contained within the cosmos. Astronomers have been able to determine that there is a hierarchal organization to the universe, with matter organized into progressively larger structures from atoms, to solar systems, to galaxies, to clusters and superclusters, to filaments, then a continued structure known as the End of Greatness.

The small-scale structure of matter and energy in the universe includes many scales of observation, ranging from subatomic particles, through stellar and solar system scales, and through the galactic scales. The large-scale structure begins at the galactic scale. Galaxies are gravitationally-bound assemblages of stars, dust, gas, radiation, and dark matter. Most contain vast numbers of star systems and are located at enormous distances from the Milky Way Galaxy, such that the light reaching Earth from these galaxies was generated billions of years ago. Galaxies are classified into four basic types including spiral galaxies, barred spiral galaxies, elliptical galaxies, and irregular galaxies.

Galaxies are organized into clusters and superclusters held together by their mutual gravitational attraction. These groups or clusters are separated by voids characterized by relatively empty space that is apparently devoid of luminous matter. The Milky Way Galaxy is part of the Local Group, which also includes the large Andromeda Spiral Galaxy, the Large and Small Magellanic Clouds, and about 20 smaller galaxies. Galaxy clusters are of several different types. Regular clusters are spherical with a dense central core and are classified based on how many galaxies reside within 1.5 megaparsecs of the cluster center. Most regular clusters have a radius between one and 10 megaparsecs and masses of 10^{15} solar masses. Irregular clusters generally have slightly lower mass (~10^{12}–10^{14} solar masses) than regular clusters and have no well-defined center. An example of an irregular cluster is the Virgo Cluster.

Galaxies and galaxy clusters are further grouped into even larger structures. Superclusters typically consist of groups or chains of clusters with masses of about 10^{16} solar masses. The Milky Way Galaxy is part of one supercluster, centered on the Virgo Cluster, and has a size of about 15 megaparsecs. In contrast, the largest known superclusters, like that associated with the Coma Cluster, are about 100 megaparsecs across. Recent advances in astronomers' ability to map the distribution of matter in space reveal that about 90 percent of all galaxies are located within a network of superclusters that permeates the known universe.

The motions of galaxies show patterns on different scales of observation. The motion of individual galaxies within clusters of galaxies appears random, but the clusters show some very ordered patterns to their motions at some of the largest scales of observation in the universe. Every known galaxy shows a redshifted spectrum, meaning they are all moving away from the Earth, in all directions. Individual galaxies that are not in clusters are moving away, as are the groups of galaxies in clusters, even though they have some random motions within the clusters. The farther away the galaxy or cluster is from Earth, the greater the redshift, and the faster it is receding. The same is true for other observational pairs—the farther apart any two galaxies or clusters are, the greater the redshift between them, showing that the entire universe is expanding like the surface of an inflating balloon.

Before 1989 astronomers thought that superclusters were the largest-scale structures in the universe. However, in 1989 a survey of redshifts by American astronomers Margaret Geller (Smithsonian Astrophysical Observatory) and John Huchra (Harvard-Smithsonian Center for Astrophysics) discovered a larger-scale structure dubbed "The Great Wall," consisting of an organized sheet of galaxies that is more than 500 million light-years long and 200 million light-years wide, yet only 15 million light-years thick. In 2003 another similar but larger sheet of galaxies, the "Sloan Great Wall," was discovered by Princeton University astronomers J. Richard Gott III and Mario Juric. This wall is 1.37 billion light-years long.

Sometimes there can be organization to emptiness. Much of the large-scale structure of the universe looks like a bubble-bath with sheets and walls of galaxies surrounding voids inside the bubbles. One of the largest known voids is the Capricornus Void, with a diameter larger than 230 million light-years. There appears to also be a hierarchal organization to voids that is only recently being observed and understood. In 2007 a possible supervoid was mapped in the constellation Eridanus by the Wilkinson Microwave Anisotropy Probe (WMAP), corresponding to the WMAP Cold Spot, a region that is cold in microwave wavelengths. The Eridanus Supervoid is about 500 million to 1 billion light-years across, making it one of the largest known structures in the universe.

Mapping the cosmic microwave background radiation, distribution of matter, energy, and light shows an overall bubble-like distribution of voids throughout the universe, separated by many sheets and filaments (string-like clusters between bubble-like voids) of galaxies, with superclusters appearing as very dense nodes, in some ways corresponding to places where three of the bubble-like voids would meet.

The "End of Greatness" proposes an even larger-scale structure to the universe at observational scales of about 300 million light-years (100 Mpc). At this scale, the lumpiness in the distribution of superclusters, the walls and filaments, and distribution of voids and supervoids all become homogenous (equal density of mass) and isotropic (similar in every direction). This largest-scale organization of the universe is consistent with models of the big bang and the inexorable expansion of the universe.

See also ASTRONOMY; ASTROPHYSICS; CONSTELLATION; COSMIC MICROWAVE BACKGROUND RADIATION; COSMOLOGY; DARK MATTER; ELECTROMAGNETIC SPECTRUM; GALAXIES; GALAXY CLUSTERS; HUBBLE, EDWIN; INTERSTELLAR MEDIUM; ORIGIN AND EVOLUTION OF THE UNIVERSE.

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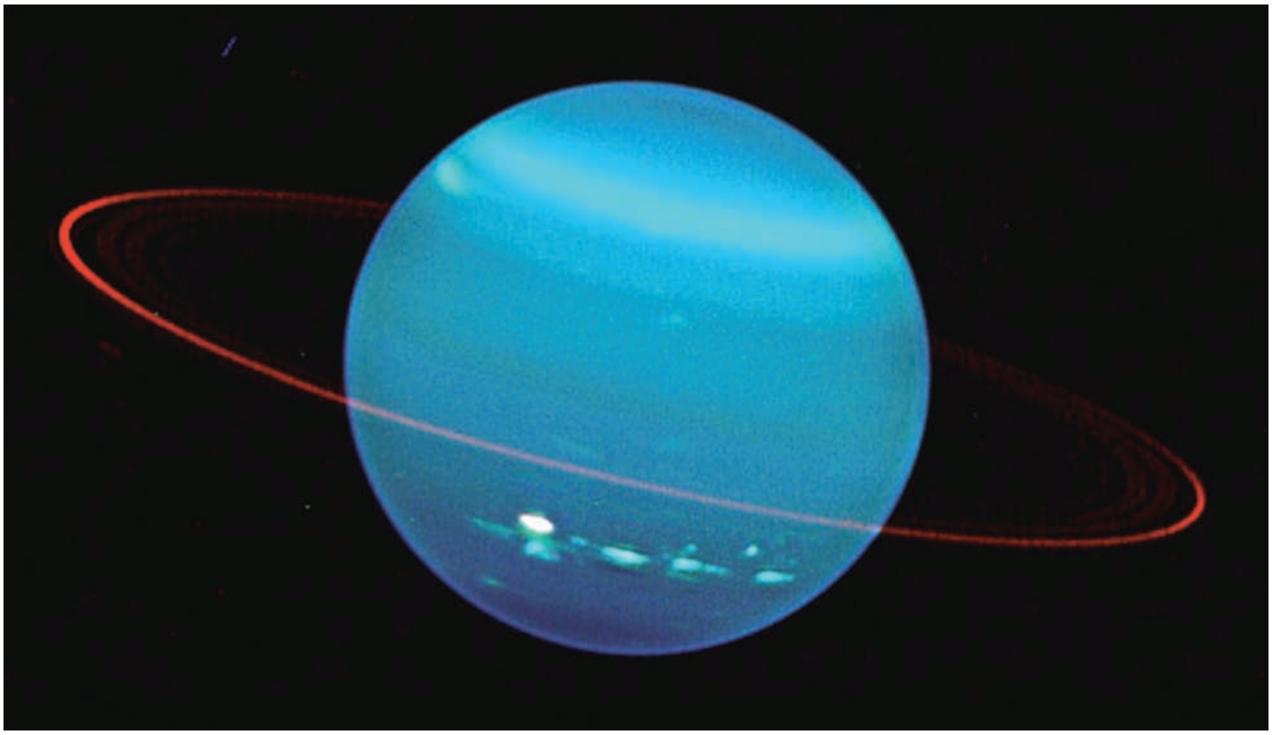
Uranus The seventh planet from the Sun, Uranus is a giant gaseous sphere with a mass 15 times that of the Earth and a diameter four times as large as Earth's (51,100 km). The equatorial plane is circled by a system of rings, some associated with the smaller of the 15 known moons circling the planet. Uranus orbits the Sun at a distance of 19.2 astronomical units (Earth-Sun distance) with a period of 84 Earth years and has a retrograde rotation of 0.69 Earth days. Its density is only 1.2 grams per cubic centimeter, compared to the Earth's average density of 5.5 grams per cubic centimeter. The density is higher, however, than Jupiter's or Saturn's, suggesting that Uranus has a proportionally larger rocky core than either one of these giant gaseous planets.

Most of the planets in the solar system have their rotational axis roughly perpendicular to the plane of the ecliptic, the plane within which the planets approximately orbit the Sun. However, the rotational axis of Uranus is one of the most unusual in the solar system as it lies roughly within the plane of the ecliptic, as if it is tipped over on its side. The cause of this unusual orientation of the planet is not known but some astronomers have speculated that it may be a result of a large impact early in the planet's history. As a consequence of this unusual orientation, as Uranus orbits the Sun, it goes through seasons where the north and south poles are alternately pointing directly at the Sun, and periods in between (spring and autumn) when the poles are aligned in between these extremes. The poles experience very long summers and winters because of the long orbital period of Uranus and are alternately plunged into icy cold darkness for 42 years, then exposed to the distant Sun for 42 years. With the rapid rotation rate and unusual orientation of the planet, an observer on the pole experiencing the change from winter to spring



Infrared image of Uranus gathered by the 10-meter Keck Telescope in Hawaii, July 11–12, 2004—Northern Hemisphere is left of rings *(California Association for Research in Astronomy/Photo Researchers, Inc.)*

would first observe the distant Sun rising above the horizon and tracing out part of a circular path, then sinking below the horizon. Eventually the Sun would finally emerge totally and trace out complete circle paths every 17 hours. The position of the Sun would progressively change over the next 42 years until it sank below the horizon for the following 42 years.

The atmosphere of Uranus is roughly similar to Jupiter's and Saturn's, consisting mostly of molecular hydrogen (84 percent), helium (14 percent), and methane (2 percent). Ammonia seems to be largely absent from the atmosphere of Uranus, part of a trend that has ammonia decreasing in abundance outward in the outer solar system, with less at lower temperatures. The reason is that ammonia freezes into ammonia ice crystals at -335°F (70 K), and Jupiter's and Saturn's upper atmospheres are warmer than this, whereas Uranus's is -355°F (58 K). Any ammonia therefore would have crystallized and fallen to the surface. The atmosphere of Uranus appears a blue-green color because of the amount of methane, but so far relatively few weather systems have been detected on the planet. Enhancement of imagery however has revealed that the atmosphere is characterized by winds that are blowing around the planet at 125 to 310 miles per hour (200–500 km/hr) in the same sense as the planet's rotation, with detectable channeling of the winds into bands. The winds are responsible for transporting heat from the warm to the cold hemisphere during the long winter months.

The magnetic field of Uranus is surprisingly strong, about 100 times as strong as the Earth's. However, since the rocky core of the planet is so far below the cloud level the strength of the magnetic field at the cloud tops on Uranus is actually similar to that on the surface of the Earth. Like the rotational axis, the orientation of the magnetic poles and field on Uranus are highly unusual. The magnetic axis is tilted at about 60° from the spin axis, and is not centered on the core of the planet, but is displaced about one-third of the planetary radius from the planet's center. The origin of these unusual magnetic field properties is not well understood, but may be related to a slurry of electrically conducting ammonia clouds near the planet's rocky surface. Whatever the cause, a similar unusual field exists on nearby Neptune.

Uranus has 15 known large moons with diameters of more than 25 miles (40 km), orbiting between 31,070 miles (50,000 km) from the planet (for the smallest moon) to 362,260 miles (583,000 km) for the largest moon. From largest to smallest, these moons include Oberon, Titania, Umbriel, Ariel, Miranda, Puck, Belinda, Rosalind, Portia, Juliet, Desdemona, Cressida, Bianca, Ophelia, and Cordelia. The 10 smallest moons all orbit inside the orbit of Miranda and are associated with the ring system around Uranus, and all of the moons rotate in the planet's equatorial plane, not the ecliptic of the solar system. Most of these moons are relatively dark, heavily cratered, and geologically inactive bodies, with the exception of Miranda, which shows a series of ridges, valleys, and different morphological terrains. One of the most unusual is a series of oval wrinkled or faulted terrains of uncertain origin, but perhaps related to subsurface magmatism, impacts, or volcanism.

The ring system around Uranus was only discovered recently, in 1977, when the planet passed in front of a bright star and the rings were observed by astronomers studying the planet's atmosphere. There are nine known rings between 27,340 and 31,690 miles (44,000–51,000 km) from the planet's center, and each of these rings appears to be made of many much smaller rings. The rings are generally dark and narrow with widths of up to six miles (10 km), with wide spaces between the main rings ranging from 125–620 miles (200–1,000 km). The rings are only a few tens of meters thick. Most of the particles that make up the rings are dust- to boulder-sized, dark-colored, and trapped in place by the gravitational forces between Uranus and its many moons.

See also EARTH; JUPITER; MARS; MERCURY; NEPTUNE; SATURN; SOLAR SYSTEM; VENUS.

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V

Venus The second planet from the Sun, Venus is the planet in our solar system that most closely resembles Earth, with a planetary radius of 3,761 miles (6,053 km), or 95 percent of the Earth's radius. Venus orbits the Sun in a nearly circular path at 0.72 astronomical units (Earth-Sun distance) and has a mass equal to 81 percent of Earth's and density of 5.2 grams per cubic centimeter, very similar to Earth's 5.5 grams per cubic centimeter. The orbital period (year) of Venus is 0.62 Earth years, but it has a retrograde rotation about its axis of 243 days, with its north pole turned essentially upside down so that its equatorial pole is inclined at 177.4° from the orbital plane. One result of this tilt and the slow retrograde rotation is that the two effects combine to make each day on Venus take the equivalent of 117 Earth days. Another effect is that the slow rotation has not set up a geodynamo current in the planet's core, so Venus has no detectable magnetic field. Thus, it lacks a magnetosphere to protect it from the solar wind, so it is constantly bombarded by high-energy particles from the Sun. These particles lead to constant ionization of the upper levels of the atmosphere. Venus is usually one of the brightest objects in the sky (excepting the Sun and Moon), and is usually visible just before sunrise or just after sunset, since its orbit is close to the Sun.

The atmosphere of Venus is very dense, is composed mostly (96.5 percent) of carbon dioxide, and is nearly opaque to visible radiation, so most observations of the planet's surface are based on radar reflectivity. Spacecraft and Earth-based observations of Venus show that the atmospheric and cloud patterns on the planet are more visible in ultraviolet (UV) wavelengths, since some of the outer clouds seem to be made of mostly sulfuric acid, which absorbs UV radiation, whereas other clouds reflect this wavelength, producing a highly contrasted image. These observations show that the atmosphere contains many large clouds moving around 250 miles per hour (400 km/hr) that rotate around the planet on average once every four days. The atmospheric patterns on Venus resemble the jet stream systems on Earth. Aside from carbon dioxide, the atmosphere contains nitrogen plus minor or trace amounts of water vapor, carbon monoxide, sulfur dioxide, and argon.

Although many basic physical Venusian properties are similar to Earth's, the atmosphere on Venus is about 90 times more massive and extends to much greater heights than Earth's atmosphere. The mass of the Venusian atmosphere causes pressures to be exceedingly high at the surface, a value of 90 bars, compared to Earth's one bar. The troposphere, or region in which the weather occurs, extends to approximately 62 miles (100 km) above the surface. The upper layers of the Venusian atmosphere, from about 75–45 miles (120–70 km) height, are composed of sulfuric acid cloud layers, underlain by a mixing zone that is underlain by a layer of sulfuric acid haze from 30–20 miles (50–30 km). Below about 18 miles (30 km) the air is clear.

The carbon dioxide–rich and water-poor nature of the Venusian atmosphere has several important consequences for the planet. First of all, these gases are greenhouse gases that trap solar infrared radiation, an effect that has raised the surface temperature to an astounding 750 K (900°F, or 475°C, and compared to 273 K for Earth). Second, surface processes are much different on Venus than Earth because of the elevated temperatures and pressures. There is no running water, rock behaves mechanically

Computer simulated view of northern hemisphere of Venus, May 26, 1993 *(NASA Jet Propulsion Laboratory)*

dissimilarly under high temperatures and pressures, and heat flow from the interior is buffered with a drastically different surface temperature.

Earth and Venus had essentially the same amounts of gaseous carbon dioxide, nitrogen, and water in their atmospheres soon after the planets formed. However, since Venus is closer to the Sun (it is 72 percent of the distance from the Sun that Earth is) it receives about two times as much solar radiation as the Earth, which is enough to prevent the oceans from condensing from vapor. Without oceans, carbon dioxide did not dissolve in seawater or combine with other ions to form carbonates, so the CO_2 and water stayed in the atmosphere. Because the water vapor was lighter than the CO_2, it rose to high atmospheric levels and was dissociated into hydrogen (H) and oxygen (O) ions; the hydrogen escaped to space, whereas the oxygen combined with other ions. Thus, oceans never formed on Venus, and the water that could have formed them dissociated and is lost in space. Earth is only slightly further from the Sun, but conditions here are exactly balanced to allow water to condense and the atmosphere to remain near the equilibrium (triple) point of solid, liquid, and vapor water. These conditions allowed life to develop on Earth, and life further modified the atmosphere-ocean system to maintain its ability to support further life. Venus never had a chance.

With Venus's thick atmosphere, the surface must be mapped with cloud-penetrating radar from Earth and spacecraft. The surface shows many remarkable features, including a division into a bimodal crustal elevation distribution reminiscent of Earth's continents and oceans. Most of the planet is topographically low, including about 27 percent flat volcanic lowlands and about 65 percent relatively flat plains, probably basaltic in composition, surrounded by volcanic flows. The plains are punctuated by thousands of volcanic structures, including volcanoes and elongate narrow flows, including one that stretches 4,225 miles (6,800 km) across the surface. Some of the volcanoes are huge, with more than 1,500 having diameters of more than 13 miles (20 km), and one (Sapas Mons) more than 250 miles (400 km) across and almost one mile (1.5 km) high. About 8 percent of the planet consists of highlands made of elevated plateaus and mountain ranges. The largest continent-like elevated landmasses include the Australian-sized Ishtar Terra in the southern hemisphere, and Africa-sized Aphrodite Terra in equatorial regions. Ishtar Terra has interior plains rimmed by what appear to be folded mountain chains and Venus's tallest mountain, Maxwell Mons, reaching 7 miles (11 km) in height above surrounding plains. Aphrodite Terra also has large areas of linear folded mountain ranges, many lava flows, and some fissures that probably formed from lava upwelling from crustal magma chambers, then collapsing back into the chamber instead of erupting.

The surface of Venus preserves numerous impact structures and unusual circular to oval structures and craters that are most likely volcanic in origin. Some of the most unusual-appearing are a series of rounded pancake-like bulges that overlap each other on a small northern hemisphere elevated terrane named Alpha Regio. These domes are about 15.5 miles (25 km) across and probably represent lava domes that filled, then had the magma withdrawn from them, forming a flat, cracked lava skin on the surface. There are many basaltic shield volcanoes scattered about the surface and some huge volcanic structures known as coronae. These are hundreds of kilometers across and are characterized by a series of circular fractures reflecting a broad upwarped dome, probably formed as a result of a plume from below. Many volcanoes dot the surface in and around coronae, and lava flows emanate and flow outward from some of them. Impact craters are known from many regions on Venus, but their abundance is much less than expected for a planet that has had no changes to its surface since formation. No impacts less than two miles (3 km) across are known since small meteorites burn up in the thick atmosphere before hitting the surface. The paucity of other larger impacts reflects the fact that the surface has been reworked and plated by basalt in the recent history of the planet, as confirmed by the abundant volcanoes, lava flows, and the atmospheric composition of the planet. It is likely that volcanism is still active on Venus.

Many of the surface features on Venus indicate some crustal movements. For instance, the folded mountain ranges show dramatic evidence of crustal shortening, and there are many regions of parallel fractures. Despite these features, there have not been any features found that are indicative of plate tectonic types of processes operating. Most of the structures could be produced by crustal downsagging or convergence between rising convective plumes, in a manner similar to that postulated for the early Earth before plate tectonics was recognized.

See also EARTH; JUPITER; MARS; MERCURY; NEPTUNE; SATURN; SOLAR SYSTEM; URANUS.

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volcano A volcano is a mountain or other constructive landform built by a singular volcanic eruption or a sequence of eruptions of molten lava and pyroclastic material from a volcanic vent. Volcanoes have many forms, ranging from simple vents in the Earth's surface, through elongate fissures that erupt magma, to tall mountains with volcanic vents near their peaks. Volcanic landforms and landscapes are as varied as the volcanic rocks and eruptions that produce them. Volcanic eruptions provide one of the most spectacular of all natural phenomena, yet they also rank among the most dangerous of geological hazards. More than 500 million people worldwide live near active volcanoes and need to understand the risk associated with volcanic eruptions and how to respond in the event of volcanic emergencies. Eruptions may send blocks of rock, ash, and gas tens of thousands of feet into the atmosphere in beautiful eruption plumes, yet individual eruptions have also killed tens of thousands of people. The hazards associated with volcanic eruptions are not limited to the immediate threat from the flowing lava and ash, but include longer-term atmospheric and climate effects and changes to land-use patterns and the livelihood of human populations.

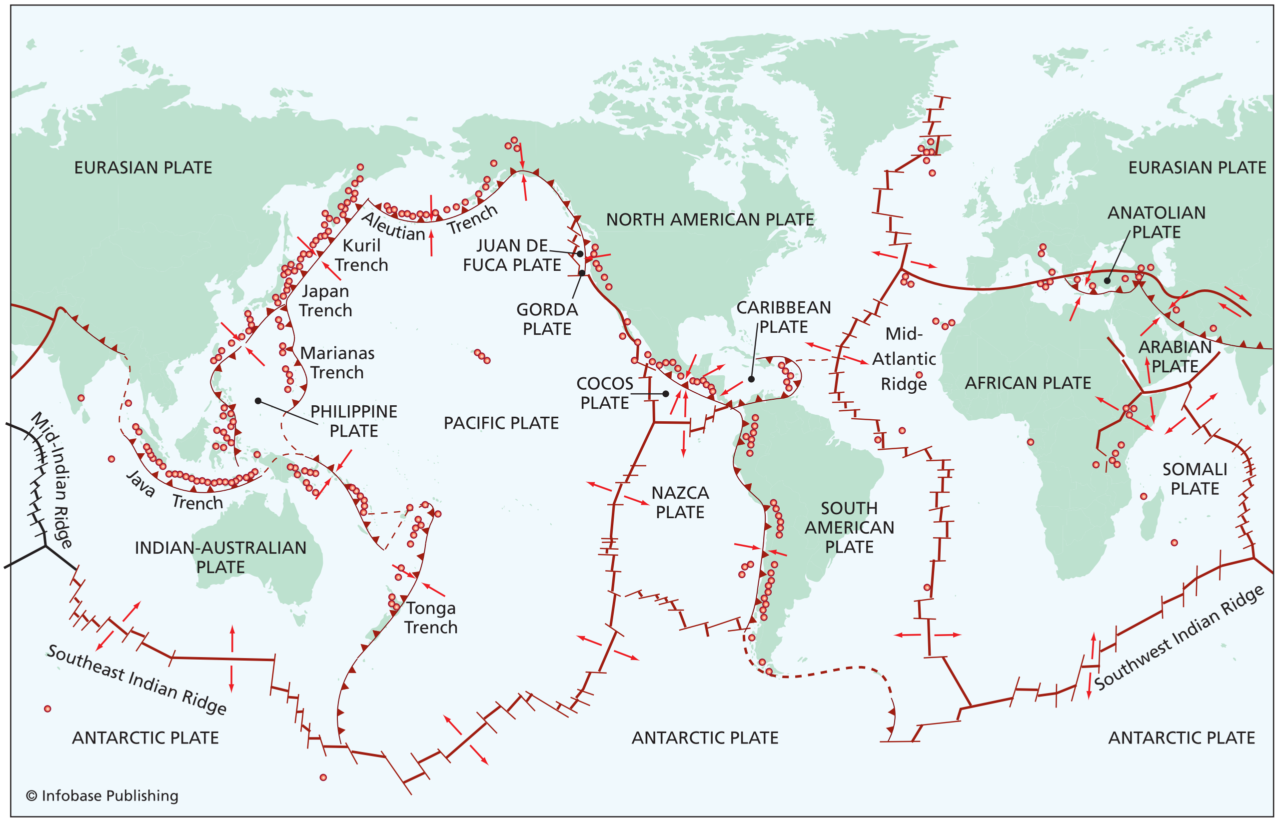
People have been awed by the power and fury of volcanoes for thousands of years, as evidenced by biblical passages referring to eruptions, and more recently by the destruction of Pompeii and Herculaneum by the eruption of Italy's Mount Vesuvius in the year 79 C.E. Sixteen thousand people died in Pompeii alone, buried by a fast-moving hot incandescent ash flow known as a nuée ardente. This famous eruption buried Pompeii in thick ash that quickly solidified and preserved the city and its inhabitants remarkably well. In the 16th century Pompeii was rediscovered and has since then been the focus of archeological investigations. Mount Vesuvius is still active, looming over the present-day city of Naples, Italy. Most residents of Naples rarely think about the threat looming over their city. There are many apparently dormant volcanoes similar to Vesuvius around the world, and people who live near these volcanoes need to understand the potential threats and hazards posed by these sleeping giants to know how to react in the event of a major eruption from the volcanoes.

VOLCANOES AND PLATE TECTONICS

Most volcanic eruptions on the planet are associated with the boundaries of tectonic plates. Extensional or divergent plate boundaries where plates are being pulled apart, such as along the mid-ocean ridges, have the greatest volume of magma erupted each year for any volcanic province on the Earth. However, these eruptions are not generally hazardous, especially since most of these eruptions occur many miles (km) below sea level. A few exceptions to this rule are noted where the mid-ocean ridges rise above sea level, such as in Iceland. There, volcanoes including the famous Hekla volcano have caused significant damage. Hekla has even erupted beneath a glacier, causing instant melting and generating fast-moving catastrophic floods called Jökulhlaups. Despite these hazards, Icelanders have learned to benefit from living in a volcanically active area, tapping a large amount of heat in geothermal power-generating systems.

Larger volcanoes are associated with extensional plate boundaries located in continents. For instance, the East African rift system is where the African continent is being ripped apart, and it hosts some spectacular volcanic cones, including Kilimanjaro, Ol Doinyo Lengai, Nyiragongo, and many others.

The most hazardous volcanoes on the planet are associated with convergent plate boundaries, where one plate is sliding beneath another in a subduction zone. The famous "Ring of Fire" rims the Pacific Ocean and refers to the ring of abundant volcanoes located above subduction zones around the Pacific Ocean. The Ring of Fire extends through the western Americas, Alaska, Kamchatka, Japan, Southeast Asia, and Indonesia. Volcanoes in this



Map of the Earth showing major plate boundaries and locations of active volcanoes

belt, including Mount Saint Helens in Washington State, typically have violent explosive eruptions that have killed many people and altered the landscape over wide regions.

An unusual style of volcanic activity is not associated with plate boundaries, but forms large broad volcanic shields in the interior of plates. These volcanoes typically have spectacular but not extremely explosive volcanic eruptions. The most famous of these "intraplate" volcanoes is Mauna Loa on Hawaii. Hazards associated with these volcanoes include lava flows and traffic jams from tourists trying to see the flows.

TYPES OF VOLCANIC ERUPTIONS AND LANDFORMS

The style of volcanic eruptions varies tremendously, both between volcanoes and from a single volcano during the course of an eruptive phase. This variety is related to the different types of magma produced by the different mechanisms described above. Geologists have found it useful to classify volcanic eruptions based on how explosive the eruption was, on which materials erupted, and by the type of landform produced by the volcanic eruption.

Tephra is material that comes out of a volcano during an eruption, and it may be thrown through the air or transported over the land as part of a hot moving flow. Tephra includes both new magma from the volcano and older broken rock fragments caught during the eruption. It includes ash and pyroclasts, rocks ejected by the volcano. Large pyroclasts are called volcanic bombs; smaller fragments are lapilli, and the smallest grade into ash.

While the most famous volcanic eruptions produce huge explosions, many eruptions are relatively quiet and nonexplosive. Nonexplosive eruptions have magma types that have low amounts of dissolved gases, and they tend to be basaltic in composition. Basalt flows easily and for long distances and tends not to have difficulty flowing out of volcanic necks. Nonexplosive eruptions may still be spectacular, as any visitor to Hawaii lucky enough to witness the fury of Pele, the Hawaiian goddess of the volcano, can testify. Mauna Loa, Kilauea, and other nonexplosive volcanoes produce a variety of eruption styles, including fast-moving flows and liquid rivers of lava, lava fountains that spew fingers of lava trailing streamers of light hundreds of feet into the air, and thick sticky lava flows that gradually creep downhill. The Hawaiians devised clever names for these flows, including *aas* for blocky rubble flows because walking across these flows in bare feet makes one exclaim "ah, ah" in pain. Pahoehoes are ropy-textured flows, after the Hawaiian term for rope.

Explosive volcanic eruptions are among the most dramatic of natural events on Earth. With little warning, long-dormant volcanoes can explode with the force of hundreds of atomic bombs, pulverizing whole mountains and sending the existing material together with millions of tons of ash into the stratosphere. Explosive volcanic eruptions tend to be associated with volcanoes that produce andesitic or rhyolitic magma and have high contents of dissolved gases. These are mostly associated with convergent plate boundaries. Volcanoes that erupt magma with high contents of dissolved gases often produce a distinctive type of volcanic rock known as pumice, which is full of bubble holes, in some cases making the rock light enough to float on water.

When the most explosive volcanoes erupt they produce huge eruption columns known as Plinian columns (named after Pliny the Elder, the Roman statesman, naturalist, and naval officer who died in 79 C.E. while struggling through thick ash while trying to rescue friends during the eruption of Mount Vesuvius). These eruption columns can reach 28 miles (45 km) in height, and they spew hot turbulent mixtures of ash, gas, and tephra into the atmosphere where winds may disperse them around the planet. Large ashfalls and tephra deposits may be spread across thousands of square miles (km^2). These explosive volcanoes also produce one of the scariest and most dangerous clouds on the planet. Nuées ardentes are hot glowing clouds of dense gas and ash that may reach temperatures of nearly 1,830°F (1,000°C), rush down volcanic flanks at 450 miles per hour (700 km/h), and travel more than 60 miles (100 km) from the volcanic vent. Nuées ardentes have been the nemesis of many a volcanologist and curious observer, as well as thousands upon thousands of unsuspecting or trusting villagers. Nuées ardentes are but one type of pyroclastic flow, which include a variety of mixtures of volcanic blocks, ash, gas, and lapilli that produce volcanic rocks called ignimbrites.

Lava fountain about 1,000 feet (304.8 m) high from Kilauea eruption, Hawaii, April 4, 1983 *(J. D. Griggs/USGS)*

Most volcanic eruptions emanate from the central vents at the top of volcanic cones. However, many other flank eruptions have been recorded, where eruptions blast out of fissures on the side of the volcano. Occasionally volcanoes blow out their sides, forming a lateral blast like the one that initiated the 1980 eruption of Mount Saint Helens in the state of Washington. This blast was so forceful that it began at the speed of sound, killing everything in the initial blast zone.

Volcanic landforms and landscapes are wonderful, dreadful, beautiful, and barren. They are as varied as the volcanic rocks and eruptions that produce them. Shield volcanoes include the largest and broadest mountains on the planet (Mauna Loa is more than 100 times as large as Mount Everest). These have slopes of only a few degrees, produced by basaltic lavas that flow long distances before cooling and solidifying. Stratovolcanoes, in contrast, are the familiar steep-sided cones like Mount Fuji, made of stickier lavas such as andesites and rhyolites, and they may have slopes of 30°. Other volcanic constructs include cinder or tephra cones, including the San Francisco Peaks in Arizona, which are loose piles of cinder and tephra. Calderas, like Crater Lake in Oregon, are huge circular depressions, often many miles (km) in diameter, that are produced when deep magma chambers under a volcano empty out (during an eruption). Such eruptions form huge empty spaces below the surface, and the overlying land collapses inward producing a topographic depression known as a caldera. Yellowstone Valley occupies one of the largest calderas in the United States. Many geysers, hot springs, and fumaroles in the valley are related to groundwater circulating to depths, being heated by shallow magma, and mixing with volcanic gases that escape through minor cracks in the crust of the Earth.

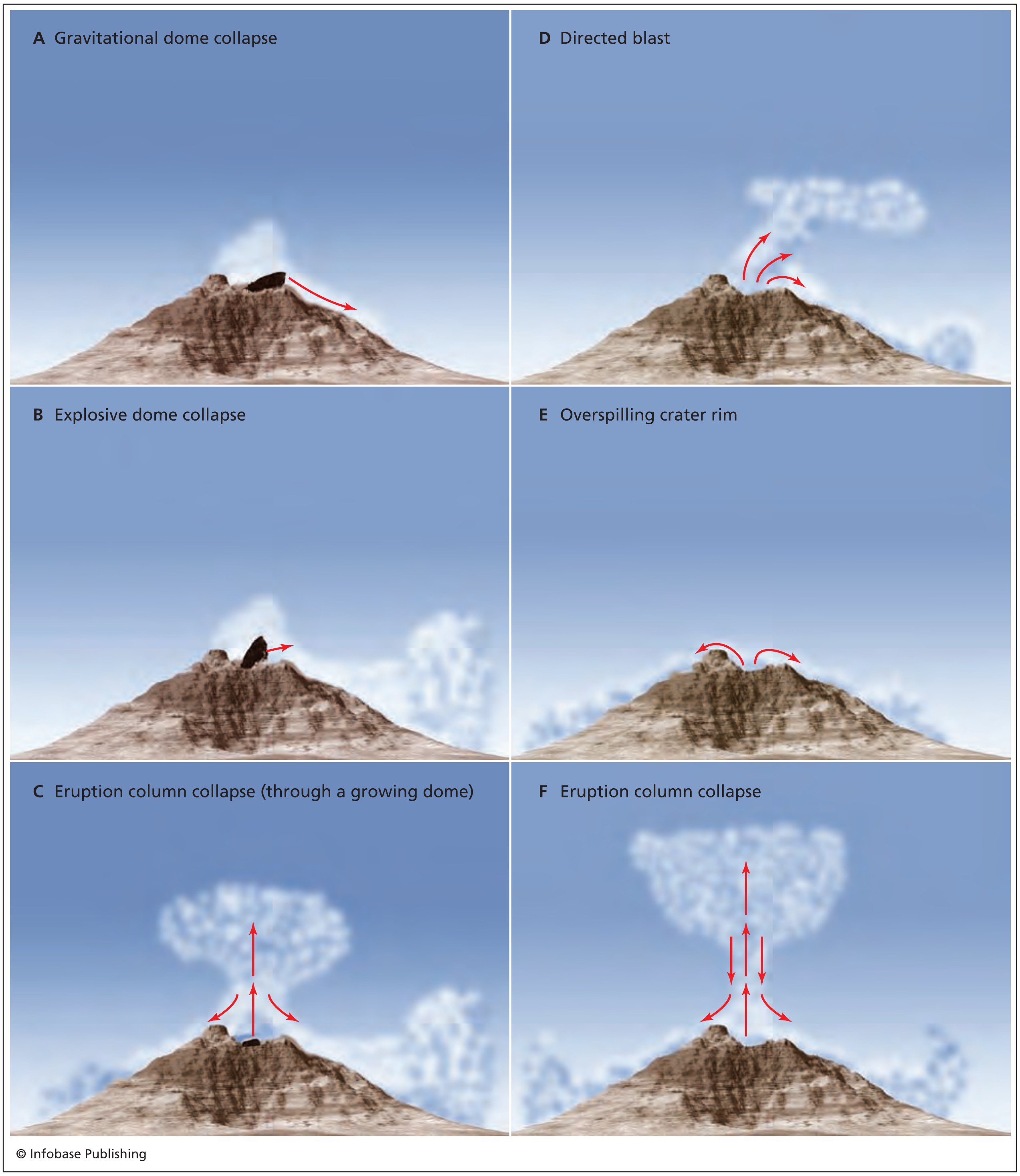


Diagram labeling parts of eruption column that may form catastrophic flows. (A) gravitational dome collapse; (B) explosive dome collapse; (C) eruption column collapse blasted through a growing dome; (D) directed blast, with Mount St. Helens as a recent example; (E) eruption overspilling crater rim; (F) eruption column collapse. If continuous this produces large volume deposits, and if discontinuous from discrete explosions, the deposits are smaller.

VOLCANISM IN RELATION TO PLATE TECTONIC SETTING

The types of volcanism and associated volcanic hazards differ in various tectonic settings because each tectonic setting produces a different type of magma, through the processes described above. Mid-ocean ridges and intraplate hot-spot types of volcanoes typically produce nonexplosive eruptions, whereas convergent tectonic margin volcanoes may produce tremendously explosive and destructive eruptions. Much of the variability in the eruption style may be related to the different types of magma produced in these different settings and also to the amount of dissolved gases, or volatiles, in these magmas. Magmas with large amounts of volatiles tend to be highly explosive, whereas magmas with low contents of dissolved volatiles tend to be nonexplosive. The difference is very much like shaking two bottles, one containing soda and one containing water. The soda contains a high concentration of dissolved volatiles (carbon dioxide) and explodes when opened. In contrast, the water has a low concentration of dissolved volatiles and does not explode when opened.

Eruptions from mid-ocean ridges are mainly basaltic flows, with low amounts of dissolved gases. These eruptions are relatively quiet, with basaltic magma flowing in underwater tubes and breaking off in bulbous shapes called pillow lavas. The eruption style in these underwater volcanoes is analogous to toothpaste being squeezed out of a tube. Eruptions from mid-ocean ridges may be observed in the few rare places where the ridges emerge above sea level, such as Iceland. Eruptions there include lava fountaining, where basaltic cinders are thrown a few hundred feet in the air and accumulate as cones of black glassy fragments, and they also include long stream-like flows of basalt.

Hot-spot volcanism tends to be much like that at mid-ocean ridges, particularly where the hot spots are located in the middle of oceanic plates. The Hawaiian Islands are the most famous hot-spot type of volcano in the world, with the active volcanoes on the island of Hawaii known as Kilauea and Mauna Loa. Mauna Loa is a huge shield volcano, characterized by a very gentle slope of a few degrees from the base to the top. This gentle slope is produced by lava flows that have a very low viscosity (meaning they flow easily) and can flow and thin out over large distances before they solidify. Magmas with high viscosity would be much stickier and would solidify in short distances, producing volcanoes with steep slopes. Measured from its base on the Pacific Ocean seafloor to its summit, Mauna Loa is the tallest mountain in the world, a fact attributed to the large distances that its low-viscosity lavas flow and to the large volume of magma produced by this hot-spot volcano.

Volcanoes associated with convergent plate boundaries produce by far the most violent and destructive eruptions. Recent convergent margin eruptions include Mount Saint Helens and two volcanoes in the Philippines, Mount Pinatubo and Mayon volcano. The magmas from these volcanoes tend to be much more viscous, are higher in silica content, and have the highest concentration of dissolved gasses. Many of the dissolved gasses and volatiles, such as water, are released from the subducting oceanic plate as high mantle temperatures heat it up as it slides beneath the convergent margin volcanoes.

VOLCANIC HAZARDS

Volcanic eruptions have been responsible for the deaths of hundreds of thousands of people, and they directly affect large portions of the world's population, land-use patterns, and climate. The worst volcanic disasters have killed tens of thousands of people, whereas others may kill only a few thousand, hundreds, or even none. The following sections discuss specific phenomena associated with volcanic eruptions that have been responsible for the greatest loss of life in individual eruptions. Understanding the hazards associated with volcanoes is important for reducing losses from future eruptions, especially considering that millions of people live close to active volcanoes. Some of the hazards are obvious, such as being overrun by lava flows, being buried by layers of ash, or being hit by hot glowing avalanche clouds known as nuées ardentes. Other hazards are less obvious, such as poisonous gases that can seep out of volcanoes, suffocating people nearby, and changes to global climate as a consequence of large volcanic eruptions. The table "Examples of Volcanic Disasters" lists examples of some of the worst volcanic disasters of the last 200 years.

Hazards of Lava Flows

In some types of volcanic eruptions lava may bubble up or effuse from volcanic vents and cracks and flow like thick water across the land surface. During other eruptions lava oozes out more slowly, producing different types of flows with different hazards. Variations in magma composition, temperature, dissolved gas content, surface slope, and other factors lead to the formation of three major types of lava flows: aa, pahoehoe, and block lava. Aas are characterized by rough surfaces of spiny and angular fragments, whereas pahoehoe have smooth ropelike or billowing surfaces. Block lavas have larger fragments than aa flows and are typically formed by stickier, more silicic (quartz rich) lavas than aa and pahoehoe flows. Some flows are transitional between these main types or may change from one type to another as surface slopes and flow rates change. It is common to see pahoehoe flows change into aa flows with increasing distance from the volcanic source.

Lava flows are most common around volcanoes that are characterized by eruptions of basalt with low contents of dissolved gasses. About 90 percent of all lava flows worldwide are made of magma with basaltic composition, followed by andesitic (8 percent) and rhyolitic (2 percent). Places with abundant basaltic flows include Hawaii, Iceland, and other exposures of oceanic islands and mid-oceanic

EXAMPLES OF VOLCANIC DISASTERS

Volcano, Location	Year	Deaths
Tambora, Indonesia	1815	92,000
Krakatau, Indonesia	1883	36,500
Mount Pelée, Martinique	1902	29,000
Nevada del Ruiz, Colombia	1985	24,000
Santa Maria, Guatemala	1902	6,000
Galunggung, Indonesia	1822	5,500
Awu, Indonesia	1826	3,000
Lamington, Papua New Guinea	1951	2,950
Agung, Indonesia	1963	1,900
El Chichon, Mexico	1982	1,700

ridges, all characterized by nonexplosive eruptions. Virtually the entire islands of the Hawaiian chain are made of a series of lava flows piled high, one on top of the other. Most other volcanic islands are similar, including the Canary Islands in the Atlantic, Reunion in the Indian Ocean, and the Galapagos in the Pacific. In January of 2002, massive lava flows were erupted from Nyiragongo volcano in Congo, devastating the town of Goma and forcing 300,000 people to flee from their homes as the lava advanced through the town.

Lava flows generally follow topography, flowing from the volcanic vents downslope in valleys, much as streams or water from a flood would travel. Some lava flows may move as fast as water, up to almost 40 miles per hour (65 km/h), on steep slopes, but most lava flows move considerably slower. More typical rates of movement are about 10 feet (several m) per hour, to 10 feet (3 m) per day for slower flows. These rates of movement of lava allow most people to move out of danger to higher ground, but lava flows are responsible for significant amounts of property damage in places like Hawaii. Lava flows also are known to bury roads, farmlands, and other low-lying areas. It must be kept in mind, however, that the entire Hawaiian island chain was built by lava flows, and the real estate that is being damaged would not even be there if it were not for the lava flows. In general, pahoehoe flows flow the fastest, aa are intermediate, and blocky flows are the slowest.

Basaltic lava is extremely hot (typically about 1,900–2,100°F, or 1,000–1,150°C) when it flows across the surface, so when it encounters buildings, trees, and other flammable objects, they typically burst into flame and are destroyed. More silicic lavas may be slightly cooler, typically in the range of 1,550–1,920°F (850–1,050°C). Most lavas will become semisolid and stop flowing at temperatures of around 1,380°F (750°C). Lavas typically cool quickly at first, until a crust or hard skin forms on the flow, then they cool much more slowly. One of the greatest hazards of lava flows is caused by this property of cooling. A lava flow may appear hard, cool, and safe to walk on, yet just below the thin surface may lay a thick layer of molten lava at temperatures of about 1,380°F (750°C). Many people have mistakenly thought it was safe to walk across a recent crusty lava flow, only to plunge through the crust to a fiery death. Thick flows may take years to crystallize and cool, and residents of some volcanic areas have learned to use the heat from flows for heating water and piping it to nearby towns.

It is significantly easier to avoid hazardous lava flows than some other volcanic hazards since in most cases it is possible to simply walk away from the hot moving lava. It is generally unwise to build or buy homes in low-lying areas adjacent to volcanoes, as these are the preferential sites for future lava flows to fill. Lava flows have been successfully diverted in a few examples in Hawaii, Iceland, and elsewhere in the world. One of the better ways is to build large barriers of rock and soil to divert the flow from its natural course to a place where it will not damage property. More creative methods have also had limited success: Lava flows have been bombed in Hawaii and Sicily, and spraying large amounts of water on active flows in Hawaii and Iceland has chilled these flows enough to stop their advance into harbors and populated areas.

Hazards of Pyroclastic Flows

While some volcanoes spew massive amounts of lava in relatively nonthreatening flows, other volcanoes are extremely explosive and send huge eruption clouds tens of thousands of feet into the air. Violent pyroclastic flows present one of the most severe hazards associated with volcanism. Unlike slow-moving lava flows, pyroclastic flows may move at hundreds of miles (km) per hour by riding on a cushion of air, burying entire villages or cities before anyone has a chance to escape. There are several varieties of pyroclastic flows and related volcanic emissions. Nuées ardentes are particularly hazardous varieties of pyroclastic flows, with temperatures that may exceed 1,470°F (800°C), and down slope velocities measured in many hundreds of miles per hour. One of the most devastating pyroclastic flows of modern time was generated from a convergent margin arc volcano in the Lesser Antilles arc on the eastern edge of the Caribbean, between North and South America. On an otherwise quiet day in 1902, the city of St. Pierre on the beautiful Caribbean island of Martinique was quickly buried by a nuée ardente from Mount Pelée that killed more than 29,000 people. Pyroclastic surges are mixtures of gas and volcanic tephra that move sideways in a turbulent mixture that may flow over topography and fill in low-lying areas. A third type of pyroclastic flow is a lateral blast, where an explosion removes large sections of a volcano and blows the material out sideways, typically with disastrous results. The May 1980 eruption of Mount Saint Helens was a laterally directed blast.

One of the most famous volcanic eruptions of all time was a pyroclastic flow. In 79 C.E., Mount Vesuvius of Italy erupted and buried the towns of Pompeii and Herculaneum under pyroclastic ash clouds, permanently encapsulating these cities and their inhabitants in volcanic ash. Later discovery and excavation of parts of these cities by archaeologists led to the world's better understanding of the horrors of being caught in a pyroclastic flow. People were found buried in ash, preserved in various poses of fear, suffocation, and running and in attempts to shelter their children from the suffocating cloud of gas and ash. Crater Lake in Oregon, the result of a pyroclastic eruption 760,000 years ago, provides a thought-provoking example of the volume of volcanic ash that may be produced. The eruption that caused this caldera to collapse covered an area of 5,000 square miles (13,000 km^2) with more than six inches (15 cm) of ash, and blanketed most of present-day Washington, Oregon, Idaho, and large parts of Montana, Nevada, British Colombia and Alberta with ash. Larger eruptions have occurred: for instance, a thick rock unit known as the Bishop tuff (a term for hardened ash) covers a large part of the southwestern United States. If any of the active volcanoes in the western United States were to produce such an eruption, it would be devastating for the economy and huge numbers of lives would be lost.

Volcanoes spew a wide variety of sizes and shapes of hardened magma and wall rock fragments during eruptions. *Tephra* is a term that is used to describe all airborne products of an eruption except for gases. Volcanic ash and material erupted during pyroclastic flows may therefore be called tephra, as are other hard objects such as volcanic bombs, blocks, and lapilli. These terms describe material that is ejected out of the volcanic vent on ballistic trajectories, potentially harming people and structures in its path or intended landing area. Volcanic bombs are clots of magma, more than 2.5 inches (6 cm) in diameter, ejected from a volcanic vent. Bombs have various shapes and sizes, with their shape being determined by magma composition, gas content, and other factors. Volcanic blocks are pieces of the wall rock plucked from the walls of the vent and sent shooting through the air by the force of the eruption. These blocks tend to retain angular and blocky shapes. Lapilli are magma clots from ash-size to 2.5 inches (up to 6 cm) in diameter ejected from the volcano and are of many shapes and internal structures as well. Many lapilli form by rain drops moving through ash clouds, causing concentric layers of ash to build around the drop and fall to the ground.

During eruptions projectiles may be thrown thousands of feet into the air and land thousands of feet from the volcanic vent. Some large volcanic bombs and blocks have been found at distances of up to several miles from their sources. Most projectiles leave the volcanic vent at speeds of 300–2,000 feet per second (100–600 m/s), and land on a near vertical trajectory, often forming impact craters where they land. The volume of projectiles landing from a volcanic vent increases toward the vent, with steep-sided volcanoes often covered by fields of projectiles that land and then fragment and roll downhill.

During eruptions large tephra clouds may explode upward and outward from the volcanic vent, expanding as the cloud incorporates more air as it rises. As it expands it becomes less dense, and the heavy particles in the clouds fall out, covering the area below the cloud with blankets of tephra. The thickest tephra blankets are deposited closest to the volcano with the fallout pattern determined by the direction of the winds that carried the tephra cloud. Tephra blankets from major eruptions may cover hundreds of thousands of square miles with volcanic ash and tephra particles. Some of this may be so thick as to collapse buildings, suffocate plants, animals, and people and sometimes may be hot enough to burn objects on impact. Tephra falls are associated with intense darkness for many hours or even days, with many historical accounts relating difficulty in seeing objects only inches from one's face. Some types of tephra are associated with high concentrations of poisonous sulfur compounds, leading to long-term crop and animal disease. Rains and wind quickly wash some tephra falls away. Other types of tephra blankets tend to form hard crusts or thick layers that solidify and become a new land surface in the affected areas.

Tephra falls tend to be so hazardous for many reasons, most relating to the size and physical characteristics of the ejecta. Eruption columns are typically 1.5–6 miles high (3–10 km) but may reach heights of more than 35 miles (55 km), covering huge areas downwind with thick layers of ash and tephra. Many falls occur rapidly, with downwind transport velocities of 5–60 miles per hour (10–100 km/hr). Ash from these clouds may be semitoxic, creating hazards to breath and for vegetation. Additionally, ash is electrically conductive and magnetic when wet, causing problems for electronics and other infrastructure.

Hazards of Mudflows, Floods, Debris Flows, and Avalanches

When pyroclastic flows and nuées ardentes move into large rivers, they quickly cool and mix with water, becoming fast-moving mudflows known as lahars. Lahars may also result from the extremely rapid melting of icecaps on volcanoes. A type of lahar in which ash, blocks of rock, trees, and other material is chaotically mixed together is known as a debris flow. Some lahars originate directly from a pyroclastic flow moving out of a volcano and into a river, whereas other lahars are secondary and form after the main eruption. These secondary, or rain-lahars, form when rain soaks volcanic ash that typically covers a region after an eruption, causing the ash to be mobilized and flow downhill into streams and rivers. It is estimated that it takes only about 30 percent water to mobilize an ash flow into a lahar. The hazards from lahars may continue for months or years after an ash fall on a volcano, as long as the ash remains in place and rains may come to remobilize the ash into flowing slurries. There is a gradual transition between pyroclastic flows, lahars, mud-laden river flows, and floods, with a progressively increasing water content and decreasing amount of suspended material. This transition generally takes place gradually as the flow moves away from the volcano. In other cases earthquakes or the collapse of crater lakes may initiate lahars, such as occurred on Mount Pinatubo during its massive 1991 eruption. Jökulhlaups, massive floods produced by volcanic eruptions beneath glaciers, are common in Iceland where volcanoes of the mid-Atlantic ridge rise to the surface but are locally covered by glaciers. Other Jökulhlaups are known to have originated beneath the snow-covered peaks of the high Andes Mountains in South America.

Lahars and mudflows were responsible for much of the burial of buildings and deaths from the trapping of automobiles during the 1980 eruption of Mount Saint Helens. Big river valleys were also filled by lahars and mudflows during the 1991 eruption of Mount Pinatubo in the Philippines, resulting in extensive property damage and loss of life. One of the greatest volcanic disasters of the 20th century resulted from the generation of a huge mudflow when the icecap on the volcano Nevado del Ruiz in Colombia catastrophically melted during the 1985 eruption. The water mixed with the volcanic ash on the slopes, forming a wet slurry that was able to flow rapidly under the force of gravity. When the mudflow moved downhill it buried the towns along the rivers leading to the volcano, killing 23,000 people and causing more than $200 million of damage to property.

Pyroclastic flows may leave thick unstable masses of unconsolidated volcanic ash that can be easily remobilized long after an eruption during heavy rains or earthquakes. These thick piles of ash may remain for many years after an eruption and not be remobilized until a hurricane or other heavy rain storm (itself a catastrophe) fluidizes the ash, initiating destructive mudflows.

The hazard potential from lahars depends on a wide range of their properties. The thicker and faster-moving lahars are the most dangerous and move the greatest distance from the volcanic source. In places where volcanoes have crater lakes, the hazard potential from lahars and floods is directly proportional to the amount of water that is stored in the lake and may be catastrophically released. Thick piles of ash and tephra may be mobilized into lahars under different conditions, depending on the size of volcanic particles, thickness of the deposits, the angle of the slope upon which they are deposited, and the amount of rain or snow that infiltrates the deposit. Communities located downhill (or down river valley) from volcanic slopes that are covered with ash need to make hazard assessments of the potential for remobilization of ash into lahars to protect citizens and property in low-lying areas.

Slope failures resulting from collapse of oversteepened volcanic constructs on volcanoes sometimes produce debris avalanches and flows that can travel large distances in very short intervals of time. Globally there are more large debris avalanche catastrophes than there are caldera collapse events. Numerous successive debris avalanche deposits, suggesting that collapse of the slopes may be one of the most important processes that modify the slopes of volcanoes, flank many volcanoes. These deposits typically consist of unsorted masses of angular to subangular fragments with hummocky surfaces. Variations in the internal structure of the deposits depend on many factors, such as the amount of air and water present in the mixture as it collapses. Water-rich debris avalanche deposits are transitional in nature with lahars. Some slope failures are associated with very dangerous lateral blasts of volcanoes, such as the 1980 eruption of Mount Saint Helens.

Hazards of Poisonous Gases

One of the lesser-known hazards of active volcanoes stems from their emission of gases. These gases normally escape through geysers, fumaroles, and fractures in the rock. In some instances, however, volcanoes emit poisonous gases, including carbon monoxide, carbon dioxide, and sulfurous gases.

These may also mix with water to produce acidic pools of hydrochloric, hydrofluoric, and sulfuric acid. Because of this, it is generally not advisable to swim in strange-colored or unusual-smelling ponds on active volcanoes.

Some of the more devastating emissions of poisonous gases such as carbon dioxide from volcanoes occurred in 1984 and 1986 in Africa. In the larger of the emissions in 1986, approximately 1,700 people and thousands of cattle were killed when a huge cloud of invisible and odorless carbon dioxide bubbled out of Lakes Nyos and Monoun in volcanic craters in Cameroon, quickly suffocating the people and animals downwind from the vent lakes. More than 3.5 billion cubic feet (100 million m^3) of gas emissions escaped without warning and spread out over the area in less than two hours, highlighting the dangers of living on and near active volcanoes. Lakes similar to Lakes Nyos and Manoun are found in many other active volcanic areas, including heavily populated parts of Japan, Zaire, and Indonesia.

Steps have recently been taken to reduce the hazards of additional gas emissions from these lakes. In 2001 a team of scientists from Cameroon, France, and the United States installed the first of a series of degassing pipes into the depths of Lake Nyos, in an attempt to release the gases from depths of the lake gradually, before they erupt catastrophically. The first pipe extends to 672 feet (205 m) deep in the lake and causes a pillar of gas-rich water to squirt up the pipe and form a fountain on the surface, slowly releasing the gas from depth. The scientific team estimates that they need five additional pipes to keep the gas at a safe level, which will cost an additional 2 million dollars.

Hazards of Volcanic-induced Earthquakes and Tsunamis

Minor earthquakes generally accompany volcanic eruptions. The earthquakes are generated by magma forcing its way upward through cracks and fissures into the volcano from the magma chamber at depth. Gas explosions in the magma conduits under the volcano generate other earthquakes. The collapse of large blocks of rock into calderas or the shifting of mass in the volcano may also initiate earthquakes. Some of these earthquakes happen with a regular frequency, or time between individual shocks, and are known as harmonic tremors. Harmonic tremors have been noted immediately before many volcanic eruptions. These earthquakes have therefore become one of the more reliable methods of predicting exactly when an eruption is imminent, as geologists can trace the movement of the magma by very detailed seismic monitoring. Harmonic tremor earthquakes typically form a continuous, low frequency rhythmic ground shaking that is distinct from the more isolated shocks associated with movement on faults. Some swarms of harmonic tremors precede an eruption by as little as a few hours or a day, and other cases are reported where the harmonic tremors have gone on for a year before the eruption. Many volcanoes are located in tectonically active areas, and these regions also experience earthquakes that are related to plate movements instead of magma movement and impending volcanic eruptions. There is an ongoing debate in the scientific community about whether or not some specific historical earthquakes and plate movements may have triggered magma migration and volcanic eruptions. For instance, the 1990 eruption of Mount Pinatubo in the Philippines was preceded by a large earthquake, but there is no direct evidence that the earthquake caused the eruption. It may, however, have opened cracks that allowed magma to rise to the surface, helping the eruption proceed.

Tsunamis, or giant seismic sea waves, may be generated by volcanic eruptions, particularly if the eruptions occur underwater. These giant waves may inundate coastlines with little warning, and tsunamis account for the greatest death toll for all volcanic hazards. For instance, in 1883 more than 36,000 people in Indonesia were killed by a tsunami generated by the eruption of Krakatau volcano. Most volcanic-induced tsunamis are produced by collapse of the upper part of the volcanic center into a caldera, displacing large amounts of water, forming a tsunami. Other volcanic tsunamis are induced by giant landslides, by volcanic-induced earthquakes, by submarine explosions, and by pyroclastic material or lahars hitting sea water. Volcanic-induced atmospheric shock waves may also initiate some tsunamis. The tsunami then moves radially away from the source at speeds of about 500 miles per hour (800 km/hr). The tsunami may have heights of a few feet at most in the open ocean and have wavelengths (distance between crests of successive waves) of a hundred or more miles (~200 km). When the tsunamis encounter and run up onto shorelines, the shape of the sea floor, bays, promontories, and the coastline helps determine the height of the wave (of course the initial height and distance also determine the height). Some bays that get progressively narrower tend to amplify the height of tsunamis, causing more destruction at their ends than their mouths.

When tsunamis strike the coastal environment, the first effect is sometimes a significant retreat or drawdown of the water level, whereas in other cases the water just starts to rise quickly. Since tsunamis have long wavelengths, it typically takes several minutes for the water to rise to its full height. Being that there is no trough right behind the crest of the wave, on account of the very long wavelength of the tsunami, the water does not recede for a considerable time after the initial crest rises onto land. The rate of rise of the water in a tsunami depends in part on the shape of the sea floor and coastline. If the sea floor rises slowly, the tsunami may crest slowly, giving people time to outrun the rising water. In other cases, especially where the sea floor rises steeply, or the shape of the bay causes the wave to be amplified, tsunamis may come crashing in huge walls of water with breaking waves that pummel the coast with a thundering roar and wreaking utmost destruction.

Because tsunamis are waves, they travel in successive crests and troughs. Many deaths in tsunami events are related to people going to the shoreline to investigate the effects of the first wave, or to rescue those injured or killed in the initial crest, only to be drowned or swept away in a succeeding crest. Tsunamis have long wavelengths, so successive waves have a long lag time between individual crests. The period of a wave is the time between the passage of individual crests, and for tsunamis the period can be an hour or more. A tsunami may therefore devastate a shoreline area and retreat, and then another crest may strike an hour later, then another, and another, in sequence.

Some of the largest recorded tsunamis have been generated by volcanic eruptions. The most famous volcanic eruption–induced tsunamis include the series of huge waves generated by the eruption of Krakatau in 1883, which reached run-up heights of more than 200 feet (60 m) and killed 36,500 people. The number of people that perished in the eruption of Santorini in 1650 B.C.E. is not known, but the toll must have been huge. The waves reached 800 feet (240 m) in height on islands close to the volcanic vent of Santorini. Flood deposits have been found 300 feet (90 m) above sea level in parts of the Mediterranean Sea and extend as far as 200 miles (320 km) southward up the Nile River. Several geologists suggest that these were formed from a tsunami generated by the eruption of Santorini. The floods from this eruption may also, according to some scientists, account for the biblical parting of the Red Sea during the exodus of the Israelites from Egypt and the destruction of the Minoan civilization of the island of Crete.

Hazards of Atmospheric Sound and Shock Waves

Large volcanic eruptions are associated with rapid expansion of gases during explosive phases, and these have been known to produce some of the loudest sounds and atmospheric pressure waves known on Earth. For instance, explosions from the 1883 eruption of Krakatau were heard almost 3,000 miles (4,700 km) away, in places as diverse as the Indian Ocean islands of Diego Garcia and Rodriguez, in south India, in southeast Asia across Myanmar, Thailand, and Vietnam, in the Philippines, and across western and central Australia. Other volcanic eruptions that produced blasts heard for hundreds to thousands of miles include the 1835 eruption of Cosiguina in Nicaragua, the eruption of Mount Pelée in 1902, and Katmai (Alaska) in 1912. Although interesting, sounds from eruptions are relatively harmless. Explosions that produce sound waves may also be associated with much more powerful atmospheric shock waves that can be destructive.

Atmospheric shock waves are produced by the pressure changes caused by the sudden explosive release of rapidly expanding steam and gases that may sometimes exceed the speed of sound. When the gas eruptions proceed at supersonic velocities (1,000–2,700 feet [305–823 m] per second depending on the temperature and density of the gas), the shock waves may be associated with huge, expanding flashing arcs of light that pulsate out of the volcano. Firsthand accounts of these flashing arcs are rare, but observations of the 1906 eruption of Vesuvius told of flashes ranging from several times a second to every few seconds. Deafening explosive sounds followed these flashes.

Large atmospheric shock waves may be powerful enough to damage or knock down buildings and may travel completely around the world. The eruptions of Krakatau in 1883, Pelée in 1902, Asama (Japan) in 1783 and 1973, and others were recorded at atmospheric weather stations around the globe. Some of these shock waves destroyed or damaged buildings across hundreds of square miles surrounding the volcano.

Many volcanic eruptions are associated with spectacular lightning storms in the ash clouds, or in the expanding gas clouds. As this material is ejected from the volcano, many particles may rub together, creating electrical discharges seen as lightning. Intense lightning storms may typically extend for 5–10 miles (8–16 km) from the eruption, posing threats to people brave enough to remain close to the eruption, as well as to communication systems. A phenomenon known as St. Elmo's fire is sometimes associated with volcanic eruptions. It refers to a glowing blue or green electrical discharge that emanates from tall objects that are near an intense electrical charge and has been observed on ships near eruptions, including Krakatau in 1883, Vesuvius in 1906, and even during the 1980 eruption of Mount Saint Helens.

Hazards from Changes in Climate

Some of the larger, more explosive volcanic eruptions spew vast amounts of ash and finer particles called aerosols into the atmosphere and stratosphere, and it may take years for these particles to settle back down to Earth. They get distributed about the planet by high-level winds, and they have the effect of blocking out some of the Sun's rays, which lowers global temperatures. This happens because particles and aerosol gases in the upper atmosphere tend to scatter sunlight back to space, lowering the amount of incoming solar energy. In contrast, particles that get injected only into the lower atmosphere absorb sunlight and contribute to greenhouse warming. A side effect is that the extra particles in the atmosphere also produce more spectacular sunsets and sunrises, as does extra pollution in the atmosphere. These effects were readily observed after the 1991 eruption of Mount Pinatubo, which spewed more than 172 billion cubic feet (5 billion m^3) of ash and aerosols into the atmosphere, causing global cooling for two years after the eruption. Even more spectacularly, the 1815 eruption of Tambora in Indonesia caused three days of total darkness for approximately 300 miles (500 km) from the volcano, and it initiated the famous "year without a summer" in Europe, because the ash from this eruption lowered global temperatures by more than a degree. Even these amounts of gases and small airborne particles are dwarfed by the amount of material placed into the atmosphere during some of Earth's largest eruptions, known as flood basalts. No flood basalts have been formed on Earth for several tens of millions of years, which is a good thing, since their eruption may be associated with severe changes in climate. For instance, 66 million years ago a huge flood basalt field was erupted over parts of what is now western India, the Seychelles Islands, and Madagascar (these places were closer together then, but since separated by plate tectonics). At this time in Earth history the climate changed drastically, and it is thought that these severe climate changes contributed to massive global extinction of most living things on Earth at the time, including the dinosaurs. The atmospheric changes stressed the global environment to such an extent that when another catastrophic event, a meteorite impact, occurred, the additional environmental stresses caused by the impact were too great for most life-forms to handle, and they died and became extinct.

Aside from global cooling or warming associated with major volcanic eruptions, volcanic gases and ash can have some severe effects on regional environmental conditions. Gases and aerosols (fine particles suspended in gas) may be acidic and may be carried far from the source as gases, aerosols, or salts, or adsorbed on the ash and tephra particles. Some of these compounds, including sulfur and chlorine, are acidic and may mix with water and other cations to form sulfuric and sulfurous acids, as well as hydrochloric acid, hydrofluoric acid, carbonic acid, and ammonia. Ash falls and rains that move through ash clouds and deposits may spread harmful and acidic fluids that may have harmful effects on vegetation, crops, and water supplies. Other volcanic eruptions have been associated with more toxic gases, such as concentrated fluorine, which has occasionally posed a volcanic hazard in Iceland.

Other Hazards and Long-Term Effects of Volcanic Eruptions

Dispersed ash may leave thin layers on agricultural fields, which may be beneficial or detrimental, depending on the composition of the ash. Much of the richest farmland on the planet is on volcanic ash layers near volcanoes. Some ash basically fertilizes soil, whereas other ash is toxic to livestock. Volcanic ash consists of tiny but jagged and rough particles that may conduct electricity when wet. These properties make ash also pose severe hazards to electronics and machinery that may last many months past an eruption. In this way ash has been known to disrupt power generation and telecommunications. The particles are abrasive and may cause serious heart and lung ailments if inhaled.

Ash clouds have some unexpected and long-term consequences to the planet and its inhabitants. Airplane pilots have sometimes mistakenly flown into ash clouds, thinking they are normal clouds, which has caused engines to fail. For instance, KLM Flight 867 with 231 people aboard flew through the ash cloud produced during the 1989 eruption of Mount Redoubt in Alaska, causing engine failure. The plane suddenly dropped two miles (3.2 km) in altitude before the pilots were able to restart the engines, narrowly averting disaster. This event led the United States Geological Survey to formulate a series of warning codes for eruptions in Alaska and their level of danger to aircraft.

After volcanic eruptions, large populations of people may be displaced from their homes and livelihoods for extended or permanent time periods. In many cases these people are placed into temporary refugee camps, which all too often become permanent shanty villages, riddled with disease, poverty, and famine. Many of the casualties from volcanic eruptions result from these long-term effects, and not the initial eruption. More needs to be done to insure that populations displaced by volcanic disasters are relocated into safe settings.

PREDICTING AND MONITORING VOLCANIC ERUPTIONS

One of the best ways to understand what to anticipate from an active volcano is to study its history. One can examine historical records to learn about geologically recent eruptions. Geological mapping and analysis can reveal what types of material the volcano has spewed forth in the more distant past.

A geologist who studies volcanic deposits can tell through examination of these deposits whether the volcano is characterized by explosive or nonexplosive eruptions, whether it has nuée ardentes or mudflows, and how frequently the volcano has erupted over long intervals of time. This type of information is crucial for estimating what the risks are for any individual volcano. Programs of risk assessment and volcanic risk–mapping need to be done around all of the nearly 600 active volcanoes on continents of the world. These risk assessments will determine which areas are prone to ash falls and which areas have been repeatedly hit by mudflows. They will help residents determine if there are any areas characterized by periodic emissions of poisonous gas. Approximately 60 eruptions occur globally every year, so these data would prove immediately useful when eruptions appear imminent.

Nearly a quarter million people have died in volcanic eruptions in the past 400 years, with a couple of dozen volcanic eruptions killing more than a thousand people each. Eruptions in remote areas have little consequence except for global climate change. In contrast, eruptions in populated areas can cause billions of dollars in damage and result in entire towns and cities being relocated. The eruption of Mount Saint Helens in 1980 caused 1 billion dollars worth of damage, and this was not even a very catastrophic eruption in terms of the volume of material emitted. The Mount Saint Helens eruption spewed about a cubic mile (4 km^3) of debris into the atmosphere, whereas 10 years later the eruption of Mount Pinatubo in the Philippines sent 5–6 cubic miles (20–25 km^3) of material skyward. The table “Catastrophic Volcanic Eruptions of the Last 200 Years” lists the deadliest volcanic eruptions of the last 200 years.

The United States Geological Survey is the main organization responsible for monitoring volcanoes and eruptions in the United States and assumes this responsibility for many other places around the world. In cases of severe eruptions or eruptions that threaten populated areas, other agencies such as the Federal Emergency Management Agency (FEMA) will join the U.S. Geological Survey and help in disseminating information and evacuating the population.

CATASTROPHIC VOLCANIC ERUPTIONS OF THE LAST 200 YEARS

Location	Year	Deaths
Tambora, Indonesia	1815	92,000
Krakatau, Indonesia	1883	36,500
Mount Pelée, Martinique	1902	32,000
Nevada del Ruiz, Colombia	1985	24,000
Unzen, Japan	1792	14,300
Laki, Iceland	1783	9,350
Kelut, Indonesia	1919	5,110
Santa Maria, Guatemala	1902	6,000
Galunggung, Indonesia	1822	5,500
Vesuvius, Italy	1631	3,500
Vesuvius, Italy	79	3,360
Awu, Indonesia	1826	3,000
Papandayan, Indonesia	1772	2,957
Lamington, Papua New Guinea	1951	2,950
El Chichon, Mexico	1982	2,000
Agung, Indonesia	1963	1,900
Sofriere, St. Vincent	1902	1,680
Oshima, Japan	1741	1,475
Asama, Japan	1783	1,377
Taal, Philippines	1911	1,335
Mayon, Philippines	1814	1,200
Agung, Indonesia	1963	1,184
Cotopaxi, Ecuador	1877	1,000
Pinatubo, Philippines	1991	800

Precursors to Eruptions

Volcanic eruptions are sometimes preceded by a number of precursory phenomena, or warnings that an eruption may be imminent. Many of these involve subtle changes in the shape or other physical characteristics of the volcano. Many volcanoes develop bulges, swells, or domes on their flanks when magma rises in the volcano before an eruption. These shape changes can be measured using sensitive devices called tilt meters, which measure tilting of the ground surface, or devices that precisely measure distances between points, such as geodolites and laser measuring devices. Bulges were measured on the flanks of Mount Saint Helens before the 1980 eruption.

Eruptions may also be preceded by other more subtle precursory events, such as increase in the temperature or heat flow from the volcano, measurable both on the surface and in crater lakes, hot springs, fumaroles, and hot springs on the volcano. There may also be detectable changes in the composition of gases emitted by the volcano, such as increases in the hydrochloric acid and sulfur dioxide gases before an eruption.

One of the most reliable precursors to an eruption is the initiation of the harmonic seismic tremors that reflect the movement of magma into the volcano. These tremors typically begin days or weeks before an eruption, and steadily change their characteristics, enabling successively more accurate predictions of how imminent the eruption is before it actually happens. Careful analysis of precursor phenomena including the harmonic tremors, change in the shape of the volcano, and emission of gases has enabled accurate prediction of volcanic eruptions, including Mount Saint Helens and Mount Pinatubo. These predictions saved innumerable lives.

Volcano Monitoring

Signs that a volcano may be about to erupt may be observed only if volcanoes are carefully and routinely monitored. Volcanic monitoring is aimed at detecting the precursory phenomena described above and tracking the movement of magma beneath volcanoes. In the United States, the United States Geological Survey is in charge of comprehensive volcano monitoring programs in the Pacific Northwest, Alaska, and Hawaii.

One of the most accurate methods of determining the position and movement of magma in volcanoes is using seismology, or the study of the passage of seismic waves through the volcano. These can be natural seismic waves generated by earthquakes beneath the volcano or seismic energy released by geologists who set off explosions and monitor how the energy propagates through the volcano. Certain types of seismic waves travel through fluids like magma (compressional- or P-waves), whereas other types of seismic waves do not (shear- or S-waves). The position of the magma beneath a volcano can be determined by detonating an explosion on one side of the volcano, and having seismic receivers placed around the volcano to determine the position of a “shadow zone” where P-waves are received, but S-waves are not. The body of magma that creates the shadow zone can be mapped out in three dimensions by using data from the numerous seismic receiver stations. Repeated experiments over time can track the movement of the magma.

Other precursory phenomena are also monitored to track their changes with time, which can further refine estimates of impending eruptions. Changes in

Arching lava fountain on Kilauea, Hawaii, February 25, 1983 *(J. D. Griggs/USGS)* the temperature of the surface can be monitored by thermal infrared satellite imagery, and other changes, such as shifts in the composition of emitted gases, are monitored. Other promising precursors may be found in changes to physical properties, such as the electrical and magnetic field around volcanoes prior to eruptions.

Changes in the geochemical nature of gases and fluids coming out of volcanic vents and fumaroles can be used as indicators of activity beneath volcanoes. These changes depend largely on the changing rates of magma degassing beneath the volcano, and interactions of the magma with the groundwater system. Monitoring of gases is largely designed to look for rapid changes or nonequilibrium conditions in hydrochloric and sulfurous acids, carbonic acids, oxygen, nitrogen, and hydrogen sulfide. Convergent margin andesitic types of explosive volcanoes show the greatest variation in composition of gases prior to eruption, since magma in these volcanoes is ultimately derived from fluids carried to depth by the subducting oceanic lithospheric slabs.

The details of geophysical volcano monitoring are complex and have undergone a rapid explosion in sophistication in recent years. One of the more common techniques in use now involves the use of a dense array or group of very sensitive seismographs called broadband seismometers that can detect a variety of different kinds of earthquakes. Broadband seismometers can detect seismic waves with frequencies of 0.1–100 seconds, a great improvement over earlier short-period seismometers that detected only frequencies between 0.1–1 second. Swarms of small earthquakes, known as harmonic tremors, are sometimes associated with the movement of magma upward or laterally beneath a volcano, and they characteristically increase in number before an eruption. These are different from tectonic earthquakes that generally follow a pattern of main shock–aftershocks. By analysis of the seismic data from the array of seismographs geologists are able to build a three-dimensional image of the area beneath the volcano, much like a tomographic image or a CAT scan, and thereby monitor the distribution and movement of magma beneath the volcano. When the magma gets closer to the surface, an eruption is more likely to occur. Movement of magma is also sometimes associated with explosion-type earthquakes, easily differentiated from earthquakes associated with movement on faults.

Many explosive volcanic eruptions are preceded by swelling, bulging, or other deformation of the ground surface on the volcano, so one method to predict eruptions involves measuring and monitoring this bulging. Ground deformation is commonly measured using a variety of devices. Some instruments precisely measure shifts in the level surface, others measure tilting, and still others make electronic distance measurements. These types of measurements have recently increased in accuracy with the advent of the use of precise Global Positioning System instruments that allow measurements of latitude, longitude, and elevation to be made that are accurate to less than a half-inch (1 cm), even in very remote locations.

Some observations have been made of phenomena that precede some eruptions, even though their cause is not clearly understood. Electrical and magnetic fields have been observed to show changes at many volcanoes, especially those with basaltic magma that has a high concentration of magnetic minerals. These changes may be related to movement of magma (and the magnetic minerals), changes in heating, movement of gases, or other causes. Recent studies have linked small changes in the microgravity fields around active volcanoes, especially explosive andesitic volcanoes, to movement of magma beneath the cones.

Satellite images are now commonly used to map volcanic deposits and features and to monitor eruptions. There is now a wide range in types of features satellites can measure and monitor, including a large range of the visible and other parts of the electromagnetic spectrum. Changes in the volcanic surface, growth of domes, and opening and closure of fissures on the volcano can be observed from satellites. Some satellites use radar technology that is able to see through clouds and some ash, and thus are particularly helpful for monitoring volcanoes in remote areas, in bad weather, at night, and during eruptions. A technique called radar interferometry can measure ground deformation at the sub-inch (cm) scale, showing bulges and swelling related to buildup of magma beneath the volcano. Some satellites can measure and monitor the temperature of the surface, and others can watch eruption plumes, ash clouds, and other atmospheric effects on a global scale.

Together all these techniques have given seismologists and geologists tools they need to make more accurate predictions of when an eruption may occur, saving lives and property. When many of the techniques are integrated into one monitoring program, then scientists are better able to predict when the next eruption may occur. Several volcano monitoring programs in the United States use many different types of observations to provide for the safety of citizens. These include the Alaskan Volcano Observatory, the Cascades Volcano Observatory, and the Hawaiian Volcano Observatory.

See also CONVERGENT PLATE MARGIN PROCESSES; ENERGY IN THE EARTH SYSTEM; GEOCHEMICAL CYCLES; MAGMA; PLATE TECTONICS; TSUNAMI, GENERATION MECHANISMS.

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W

weathering Weathering is the process of mechanical and chemical alteration of rock marked by the interaction of the lithosphere, atmosphere, hydrosphere, and biosphere. The resistance to weathering varies with climate, composition, texture, and how much a rock is exposed to the elements of weather. Weathering processes occur at the lithosphere/atmosphere interface. This is actually a zone that extends down into the ground to the depth that air and water can penetrate—in some regions this is a few feet (meters), in others it is a mile (kilometer) or more. In this zone, the rocks make up a porous network, with air and water migrating through cracks, fractures, and pore space. The effects of weathering can often be seen in outcrops on the sides of roads, where they cut through the zone of alteration into underlying bedrock. These roadcuts and weathered outcroppings of rock show some similar properties. The upper zone near the surface is made of soil or regolith in which the texture of the fresh rock is not apparent, a middle zone in which the rock is altered but retains some of its organized appearance, and a lower zone, of fresh unaltered bedrock.

PROCESSES OF WEATHERING

There are three main types of weathering. Chemical weathering, the decomposition of rocks through the alteration of individual mineral grains, is a common process in the soil profile. Mechanical weathering is the disintegration of rocks, generally by abrasion. Mechanical weathering is common in the talus slopes at the bottom of mountains, along beaches, and along river bottoms. Biological weathering involves the breaking down of rocks and minerals by biological agents. Some organisms attack rocks for nutritional purposes; for instance, chitons bore holes through limestone along the seashore, extracting their nutrients from the rock.

Generally, mechanical and chemical weathering are the most important, and they work hand-in-hand to break down rocks into the regolith. The combination of chemical, mechanical, and biological weathering produces soils, or a weathering profile.

Mechanical Weathering

There are several different types of mechanical weathering which may act separately or together to break down rocks. The most common process of mechanical weathering is abrasion, where movement of rock particles in streams, along beaches, in deserts, or along the bases of slopes causes fragments to knock into each other. These collisions cause small pieces of each rock particle to break off, gradually rounding the particles and making them smaller, and creating more surface area for processes of chemical weathering to act upon.

Some rocks develop joints, or parallel sets of fractures, from differential cooling, the pressures exerted by overlying rocks, or tectonic forces. Joints are fractures along which no observable movement has occurred. Joints promote weathering in two ways: they are planes of weakness across which the rock can break easily, and they act as passageways for fluids to percolate along, promoting chemical weathering.

Crystal growth may aid mechanical weathering. When water percolates through joints or fractures, it can precipitate minerals such as salts, which grow larger and exert large pressures on the rock along the joint planes. If the blocks of rock are close enough to a free surface such as a cliff, large pieces of rock may be forced off in a rockfall, initiated by the gradual growth of small crystals along joints.

Sheets of granite carved by Tuolumne River and ancient glaciers in Yosemite National Park, California *(Joseph H. Bailey/National Geographic/Getty Images)*

When water freezes to form ice, its volume increases by 9 percent. Water is constantly seeping into the open spaces provided by joints in rocks. When water filling the space in a joint freezes, it exerts large pressures on the surrounding rock. These forces are very effective agents of mechanical weathering, especially in areas with freeze-thaw cycles. They are responsible for most rock debris on talus slopes of mountains and cracks in concrete in areas with cold climates.

Heat may also aid mechanical weathering, especially in desert regions where the daily temperature range may be extreme. Rapid heating and cooling of rocks sometimes exerts enough pressure on the rocks to shatter them to pieces, thus breaking large rocks into smaller fragments.

Plants and animals may also aid mechanical weathering. Plants grow in cracks and push rocks apart. This process may be accelerated if plants such as trees become uprooted, or blown over by wind, exposing more of the underlying rock to erosion. Burrowing animals, worms, and other organisms bring an enormous amount of chemically weathered soil to the surface, and continually turn the soils over and over, greatly assisting the weathering process.

Chemical Weathering

Minerals that form in igneous and metamorphic rocks at high temperatures and pressures may be unstable at temperatures and pressures at the Earth's surface, so they react with the water and atmosphere to produce new minerals. This process is known as chemical weathering. The most effective chemical agents are weakly acidic solutions in water. Therefore, chemical weathering is most effective in hot and wet climates.

Rainwater mixes with CO_2 from the atmosphere and from decaying organic matter, including smog, to produce carbonic acid according to the following reaction:

$$H_2O + CO_2 \rightarrow H_2CO_3$$

$$\text{Water + carbon dioxide} \rightarrow \text{carbonic acid}$$

Carbonic acid ionizes to produce the hydrogen ion (H^+), which readily combines with rock forming minerals to produce alteration products. These alteration products may then rest in place and become soils, or be eroded and accumulate somewhere else.

Hydrolysis is a process that occurs when the hydrogen ion from carbonic acid combines with potassium feldspar to produce kaolinite, a clay mineral, according to the following reaction:

$$2KAlSi_3O_8 + 2H_2CO_3 + H_2O \rightarrow$$
$$Al_2Si_2O_5(OH)_4 + 4SiO_2 + 2K^{+1} + 2HCO_3$$

feldspar + carbonic acid + water →
kaolinite + silica + potassium + bicarbonate ion

This reaction is one of the most important reactions in chemical weathering. The product, kaolinite, is common in soils and is virtually insoluble in water. The other products, silica, potassium, and bicarbonate are typically dissolved in water and carried away during weathering.

Much of the material produced during chemical weathering is carried away in solution and deposited elsewhere, such as in the sea. The highest-temperature minerals are leached the most easily. Many minerals combine with oxygen in the atmosphere to form another mineral by oxidation. Iron is very easily oxidized from the Fe+2 state to the Fe+3 state, forming goethite or with the release of water, hematite.

$$2FeO + (OH)_2 \rightarrow Fe_2O_3 + H_2O$$

Different types of rock weather in distinct ways. For instance, granite contains potassium feldspar and weathers to form clays. Building stones are selected to resist weathering in different climates, but now, increasing acidic pollution is destroying many old landmarks. Chemical weathering results in the removal of unstable minerals and a consequent concentration of stable minerals. Included in the remains are quartz, clay, and other rare minerals such as gold and diamonds, which may be physically concentrated in placer deposits.

On many boulders, weathering penetrates only a fraction of the diameter of the boulder, resulting in a rind of the altered products of the core. The thickness of the rind itself is useful for knowing the age of the boulder, if rates of weathering are known. These types of weathering rinds are useful for determining the age of rockslides and rockfalls and the time interval between rockfalls in any specific area.

Exfoliation is a weathering process where rocks spall off in successive shells, like the skin of an onion. Exfoliation is caused by differential stresses within a rock formed during chemical weathering processes. For instance, feldspar weathers to clay minerals, which take up a larger volume than the original feldspar. When the feldspar minerals turn to clay, they exert considerable outward stress on the surrounding rock, which is able to form fractures parallel to the rock's surface. This need for increased space is accommodated by the minerals through the formation of these fractures, and the rocks on the hillslope or mountain are then detached from their base and more susceptible to sliding or falling in a mass-wasting event.

If weathering proceeds along two or more sets of joints in the subsurface, it may result in shells of weathered rock which surround unaltered rocks, looking like boulders. This is known as spheroidal weathering. The presence of the several sets of joint surfaces increases the effectiveness of chemical weathering, because the joints increase the available surface area to be acted on by chemical processes. The more subdivisions within a given volume, the greater the surface area.

Biological Weathering

Biological weathering is the least important of the different categories of weathering. In some places plants and microorganisms may derive nutrition from dissolving minerals in rocks and soil, thus contributing to their breakdown and weathering. There are enormous numbers of microorganisms and insects living in the soil horizon, and these contribute to the breakdown of organic material in the soils and also contribute their tests or bodies when they die. Biological weathering may also include some of the effects of roots pushing rocks apart or expanding cracks in the weathered rock horizon. These effects also move rock fragments, so they are discussed under the topic of mechanical weathering.

FACTORS THAT INFLUENCE WEATHERING

The effectiveness of weathering processes is dependent upon several different factors, explaining why some rocks weather one way at one location and a different way in another location. Rock type is an important factor in determining the weathering characteristics of a hillslope, because different minerals react differently to the same weathering conditions. For instance, quartz is resistant to weathering, and quartz-rich rocks typically form large mountain ridges. Conversely, shales readily weather to clay minerals, which are easily washed away by water, so shale-rich rocks often occupy the bottoms of valleys. Examples of topography being closely related to the underlying geology in this manner are abundant in the Appalachians, Rocky Mountains, and most other mountain belts of the world.

Rock texture and structure is important in determining the weathering characteristics of a rock mass. Joints and other weaknesses promote weathering by increasing the surface area for chemical reactions to take place on, as described above. They also allow water, roots, and mineral precipitates to penetrate deeply into a rock mass, exerting outward pressures that can break off pieces of the rock mass in catastrophic rockfalls and rockslides.

The slope of a hillside is important for determining what types of weathering and mass-wasting processes occur on that slope. Steep slopes let the products of weathering get washed away, whereas gentle slopes promote stagnation and the formation of deep weathered horizons.

Climate is one of the most important factors in determining how a site weathers. Moisture and heat promote chemical reactions, so chemical weathering processes are strong and fast and dominate over mechanical processes in hot, wet climates. In cold climates, chemical weathering is much less important. Mechanical weathering is very active during freezing and thawing, so mechanical processes such as ice wedging tend to dominate over chemical processes in cold climates. These differences are exemplified by two examples of weathering. In much of New England, a hike over mountain ridges will reveal fine, millimeter-thick striations that were formed by glaciers moving over the region more than 10,000 years ago. Chemical weathering has not removed even these one-millimeter-thick marks in 10,000 years. In contrast, new construction sites in the Tropics, such as roads cut through mountains, often expose fresh bedrock. In a matter of 10 years these road cuts will be so deeply eroded to a red soil-like material, called gruse, that the original rock will not be recognizable.

As in most things, time is important. It takes tens of thousands of years to wash away glacial grooves in cold climates, but in the Tropics, weathered horizons that extend to hundreds of meters may form over a few million years.

See also ATMOSPHERE; HYDROSPHERE; SOILS.

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Wegener, Alfred Lothar **(1880–1930) German *Meteorologist, Geologist*** Alfred Lothar Wegener was born on November 1, 1880, in Berlin, Germany, and obtained a Ph.D. in astronomy from the University of Berlin in 1904. He is well known for his studies in meteorology and geophysics and is considered by many to be the father of the theory of continental drift. His is also known for his work on dynamics and thermodynamics of the atmosphere, atmospheric refraction and mirages, optical phenomena in clouds, acoustical waves, and the design of geophysical instruments. Wegener was an avid balloonist, and pioneered the use of weather balloons to monitor weather and air masses while he was working at the Royal Prussian Aeronautical Observatory near Berlin. Alfred and his brother, Kurt, broke a world endurance record for hot-air balloons in 1906, staying aloft for more than 52 hours. Alfred married the daughter of famous Russian climatologist Vladdimir Koppen. On his fourth and last expedition to Greenland, Alfred and his companion Rasmus Villumsen became lost in a blizzard on November 2, 1930, and Wegener's body was not discovered until May 12, 1931.

Alfred Wegener's interest in meteorology and geology led him on a Danish expedition to the unmapped northeastern Greenland coast in 1906–08, mainly to study the circulation of polar air masses. This was the first of four Greenland expeditions he would make, and this area remained one of his dominant interests. In 1909 he took a position at the University of Marburg in Germany, where he lectured on meteorology, astronomy, and mapping. He authored a textbook in meteorology called *The Thermodynamics of the Atmosphere,* based on a series of lectures he gave at the university, and published it in 1911, when he was just 30 years old.

Wegener is most famous for being the first person to come up with the idea for continental drift. This interest was initially sparked while he was teaching at the University of Marburg in 1911 and noted the striking similarity of fossils from continents now separated by large oceans. The accepted theories for this similarity at the time were that land bridges between the continents occasionally rose up, allowing plants and animals to move from continent to continent. However, Wegener studied the apparent correspondence between the shapes of the coastlines of western Africa and eastern South America, and he hypothesized that the continents had themselves moved apart and that land bridges did not rise between stationary continents. Soon, he came up with a model in which most of the world's continents had drifted away from a former supercontinent starting around 180 million years ago. He continued to study the paleontological and geologic evidence, concluding that these similarities demanded a detailed explanation.

In 1912 Wegener returned to Greenland, on a perilous journey in which the team "narrowly escaped death" while climbing a tidewater glacier on the coast that suddenly began calving, and then he became the first person to spend the entire winter on the ice cap. In the spring the team broke another record, making the longest crossing of the ice sheet ever, walking 750 miles (1,200 km) across barren ice at elevations up to 10,000 feet (3,000 m). During this trip Wegener collected many scientific samples and data on glaciers and climate and became the first person to track storms over the polar ice cap.

Wegener continued to study many different features on the continents when he returned to Marburg and found that mountain ranges in South America

Alfred Wegener with pipe and parka *(Alfred-Wegener-Institut, Germany)*

and Africa lined up if the continents were once together, and belts of distinctive rock types, such as coal, also matched on different continents if they were restored to his hypothesized supercontinent of Pangaea (meaning all land). Alfred Wegener studied the fossils and found that narrow belts of distinctive fauna and flora, such as the reptiles *Mesosaurus* and *Lystrosaurus,* matched on the former supercontinent and that the *Glossopteris* flora from the southern continents also matched on his restored Pangaea map. Wegener wrote an extended account of his continental drift theory in his 1915 book *Die Entstehung der Kontinente und Ozeane* (*The Origin of the Continents and Oceans,* translated into English in 1966). In this book, he argued strongly against the land bridge hypothesis, stating that continents are made of different material (granite) that is less dense than the oceanic crust (made of basalt), and that the weaker material should be floating on the denser substratum much like an iceberg on water. He also provided evidence of the continents moving up and down relative to sea level, noting that the continents in northern latitudes rise up when glaciers retreat from an area, rising or rebounding in response to the reduction of weight on the crust. He reasoned that the continents must also be moving laterally, explaining why coastlines of different continents could be restored so perfectly.

Wegener also argued against the then leading model for the origins of mountains. Others, such as the Tasmanian geologist S. Warren Carey, advocated that mountains formed by the cooling and shrinking of the Earth and that as the Earth shrunk mountains formed as wrinkles to accommodate the change in surface area. Wegener said that model did not account for the distribution and spacing of mountain ranges. He argued instead that they formed on the edges of continents that had drifted and collided with other continents, such as where India was currently crashing into Asia.

As a meteorologist he began to look at ancient climates, using paleoclimatic evidence he found to strengthen his theory of continental drift. One of his strongest arguments was that of the patterns of the Permian-Carboniferous glaciation on Pangaea. If the continents were restored, the paleoglaciers would have a pattern of all the ice moving away from a central core near the South Pole about 280 million years ago, whereas if the continents had their present distribution, then the glaciation patterns would be random and would require more water to make the amount of ice needed to explain the patterns than is available on Earth.

Wegener was by no means the first to think of the theory of continental drift. However, he was the first to go to great lengths to develop and establish the theory. His ideas were met for the large part by the geological community with strong opposition, anger, and hostility. Many geologists noted that Wegener was not trained as a geologist, so did not believe him, and published many disparaging comments on his theory and even his personality. Wegener had evidence for continental drift but could not provide a mechanism. Without a driving force he could do little to argue against those who said there was no driving mechanism, except to smoke his famous pipe and remain silent. He did argue, however, for the validity of his observations, especially that the continents move, that the movement causes deformation at their edges, and that earthquakes and volcanoes are associated with the edges of these great moving continents. It was not until 40–50 years later that proof of Wegener's theories came, in the form of the many proofs of plate tectonics that came with the geological revolution in the 1960s.

Wegener made his fourth and final trip to Greenland in the spring of 1930, never to return. The expedition started with 22 scientists and technicians, but bad weather plagued and delayed the initial setup of the base camp from May until mid-June, and the inland camp at Eismitte had only basic supplies. On September 21 Wegener led a team of 15 dogsleds to bring supplies to Eismitte, but bad weather convinced 12 of the 13 local Greenlanders to turn back after one week. After 40 days of traveling, Wegener and his two remaining companions reached Eismitte, delivered the supplies, and then celebrated Wegener's 50th birthday on November 1st. The next day Alfred and Rasmus Villumsen, his Greenlander companion, set out to return to base camp, but never arrived. In the spring, on May 12 a search party found Wegener's body, buried in the snow in sleeping bags, and they concluded he died of a heart attack in his sleep, from exertion of the trip. Villumsen was never found. His friends and companions erected an ice mausoleum over Wegener's body, all of which have since been covered deeply in the snow and ice of the glacier, and Wegener's body has become part of the glacial ice cap he devoted much of his life to studying.

See also GONDWANA, GONDWANALAND; HISTORICAL GEOLOGY; PLATE TECTONICS; SUPERCONTINENT CYCLES.

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Werner, Abraham Gottlob (1749–1817) Prussian, German *Geologist, Mineralogist* Abraham Werner was enormously influential in the field of geology. Werner developed techniques for identifying minerals using human senses, and this appealed to a broad audience interested in learning more about geology. Werner also proposed a new classification for certain geologic formations. In the 18th century, rocks were explained and were classified into three categories with accordance to the "biblical flood," including Primary for ancient rocks without fossils (believed to precede the flood), Secondary for rocks containing fossils (often attributed to the flood itself), and Tertiary for sediments believed to have been deposited after the flood. Werner did not dispute the commonly held belief of the biblical flood, but he did discover a different group of rocks that did not fit this classification—rocks with a few fossils that were younger than primary rocks but older than secondary rocks. He called these "transition" rocks. Geologists of succeeding generations classified these rocks into the geologic periods still accepted today. Werner is the father of the discredited school of thought called Neptunism, that proposed that granitic rocks crystallized from mineralized fluids in the early Earth's oceans.

Abraham Gottlob Werner was born in Wehrau of Prussian Silesia in southeastern Germany on September 25, 1749. He was born into a mining family, and his father was a foreman at the foundry in Wehrau. Educated at Freiberg and Leipzig, Werner studied law and mining, then became an inspector and teacher of mining and mineralogy at the influential Freiberg Mining Academy in 1775. When he was studying at Leipzig in 1774, Werner wrote his first book on mineralogy, *Vonden äusserlichen Kennzeichen der Fossilien* (On the external characters of fossils, or of minerals), a book that became influential in its field. Werner did not publish many books or works after this, but instead was known through his lecturing, his mentoring of students, and many interactions with colleagues. Werner was plagued with health problems his entire life and rarely traveled; he spent his time quietly near Freiberg. When he was young he enjoyed mineral collecting, but as age and disease took their toll he abandoned field work. He died in Dresden on June 30, 1817.

Werner was one of the most important geologists of his time, in an era when the geologic and scientific community was actively presenting evidence that the geologic record preserves a history of the Earth that is very different from that advocated by the church at that time. Werner divided the strata of Europe and the world into five main series, including the Primitive, Transition, Secondary (or stratified), Alluvial (or Tertiary), and Volcanic (or Younger). His theory of neptunism, which was advocated by the church, was based on his idea that the early Primitive granites were crystallized from the sea before land had emerged from the worldwide ocean. Neptune was the Roman name for the ancient Greek god of the sea, Poseidon, and Werner's belief that nearly all rocks could be explained as precipitates from the ocean led to his theory's being called neptunism. Werner's Transition series included limestones, dikes, sills, and graywackes, which he suggested were universal formations that extended around the entire world. These were followed by the Secondary or Stratified series, including layered fossiliferous rocks and lava flows. Werner interpreted these to reflect the emergence of mountains from the primeval sea, depositing the products of their erosion on their flanks. These are followed by the Alluvial or Tertiary rocks consisting of poorly consolidated sands, gravels, and clays deposited as the oceans withdrew and receded from the continents. Finally, the Volcanic series consisted of younger lava flows associated with volcanic vents that Werner suggested were the product of subterranean coal fires.

Werner's ideas were debated, particularly his ideas on the origin of granites and basalts. Many other geologists noted that volcanic rocks occurred in places not known to have coal beds and thought they may have formed from melts of rock at depth. This alternate school of thought, called plutonism, pioneered by James Hutton, later became dominant and is accepted today along with the school of thought called uniformitarianism, whereby processes observed to create specific effects on the modern Earth may be assumed to be responsible for creating similar effects in the geological record. Werner was also criticized on the basis that the volume of water required by his theory for a universal ocean was enormous. He managed to avoid this question somewhat by suggesting many of the waters escaped or evaporated to space.

See also HISTORICAL GEOLOGY; HUTTON, JAMES; ORIGIN AND EVOLUTION OF THE EARTH AND SOLAR SYSTEM.

Appendix I

Chronology

ca. 5000 B.C.E.	Egyptians develop the balance and a standard unit of weight.
ca. 3000 B.C.E.	Egyptians develop a standard unit of length.
ca. 1450 B.C.E.	Egyptians develop the water clock.
ca. 1150 B.C.E.	The first geologic map, the Turin papyrus, is made in Egypt to help mine gold deposits.
ca. 550 B.C.E.	Pythagoras, in Greece, studies acoustics, relating the pitch of a tone to the length of the wind instrument or of the string producing it.
ca. 400 B.C.E.	Democritus, in Greece, states that all matter is made up of “atoms” and empty space.
ca. 370 B.C.E.	Aristotle, in Greece, describes free fall, but incorrectly claims that heavier bodies fall faster than lighter ones.
ca. 350 B.C.E.	Aristotle, in Greece, notes the slow rates of geologic processes such as erosion.
ca. 300 B.C.E.	Theophrastus, Greek scientist, publishes “On Stones,” including one of the first systematic descriptions and classification of minerals, ores, and their behavior under specific tests such as burning.
ca. 270 B.C.E.	Ctesibius of Alexandria, Egypt, invents an accurate water clock, in use until the Renaissance.
ca. 260 B.C.E.	Archimedes, in Greece, studies floating bodies and states his principle of buoyancy. He also states the law of the lever.
ca. 130 B.C.E.	Hipparchus, from Greece, uses trigonometry to measure the sizes and distance to the Sun and Moon, and orbit of the Moon around Earth.
ca. 60 B.C.E.	Lucretius, in Greece, proposes the atomic nature of matter.
ca. 62 C.E.	Hero of Alexandria, Egypt, studies air pressure and vacuum.
ca. 50–70	Pliny the Elder publishes *Historia Naturalis* in 37 volumes. In these works he described many new minerals and ores, and defined the basis of crystallography.
ca. 110–50	In Greece, Ptolemy publishes *Almagest,* the first complete record of astronomy. This was followed by his *Geographia,* which discussed the geography of the Greco-Roman world, and *Tetrabiblos,* a discourse on astrology and natural philosophy.
ca. 700	I Hsing, in China, develops a mechanical clock.
ca. 1000	Jabir ibn Hayyan, Persian polymath, publishes on the geology of India, including the recognition that many of the rocks there were initially deposited deep under the seas.
ca. 1010	Ibn Sina (Avicenna in Latinized form), a Persian polymath, publishes *Kitab al-Shifa* (the Book of Cure, Healing or Remedy from ignorance), containing some of the early and influential works on Mineralogy and Meteorology, in six chapters: Formation of mountains; The advantages of mountains in the formation of clouds; Sources of water; Origin of earthquakes; Formation of minerals; and The diversity of earth’s terrain. Many of these contributed to later theories of uniformitarianism, the law of superposition, and catastrophism.
ca. 1080	Shen Kuo (also known as Mengxi), Chinese polymath, formulates a theory of geomorphology, including deposition, uplift, erosion, and the

role of climate change, in studies of the Taihang Mountains of China.

ca. 1100 Abu'L-Fath 'Abd al-Rahman al-Khazini, in Persia, proposes that gravity acts toward the center of Earth.

ca. 1100 Maimonides (Rabbi Moshe ben Maimon) publishes The Guide for the Perplexed, including expositions on the Aristotelian geocentric models for the universe, but with a constantly changing universe.

ca. 1200 Jordanus de Nemore, in Germany, studies motion and explains the lever.

ca. 1235 Roger Bacon emphasizes the importance of experimentation.

1276 Roger Bacon, in England, proposes using lenses to correct vision.

1284 Witelo, in Poland, describes reflection and refraction of light.

1300 Rabbi Issac of Akko estimates the age of the universe to be 13.34 billion years old.

1305 Dietrich von Freiberg, in Germany, describes and explains rainbows.

1543 Nicolaus Copernicus publishes *De revolutionibus orbium coelestium,* recognizing that the Earth is not the center of the universe and that the solar system is heliocentric, with the Sun at the center.

1546 Niccolò Tartaglia, in Italy, studies projectile motion and describes the trajectory of a bullet.

1563 Tycho Brahe publishes his *Ephemeris,* tables of predictions of the locations of the stars, planets, and constellations.

1572 Tycho Brahe observes a supernova in the constellation Cassiopeia, changing the views that the heavens were unchanging.

1582 Galileo Galilei, in Italy, describes the motion of a pendulum, noticing that its period is constant and, for small amplitudes, independent of amplitude.

1583–86 Flemish scientist Simon Stevin investigates hydrostatics and free fall.

1590–95 Zacharias Janssen makes the first microscope.

1590–91 Galileo investigates falling bodies and free fall.

1596 Johannes Kepler publishes his work *Mysterium Cosmographicum,* a geometric model of a geocentric universe.

1600s Galileo develops the principle of inertia.

1600 English scientist William Gilbert studies magnetism and its relation to electricity and describes Earth as a magnet.

1601 Tycho Brahe suddenly dies. Some theories suggest he was murdered by Johannes Kepler, who took over his position and research.

1604 Johannes Kepler publishes observations of supernovas.

1609 Dutch lens maker Hans Lippershey invents the telescope. German astronomer Johannes Kepler presents his first and second laws of planetary motion.

1610 Galileo Galilei publishes his observations of several moons of Jupiter and uses this to argue for a Sun-centered model for the universe.

1617–21 Johannes Kepler publishes his *Epitome astronomia Copernicanae* (Epitome of Copernican astronomy), including the heliocentric model for the universe, the elliptical paths of planets, and all three laws of planetary motion.

1622 Willebrord Snell presents his law of refraction of light.

1636 French mathematician René Descartes advances understanding of rainbows.

1638 Galileo studies motion and friction.

1657 Christian Huygens publishes the first book on probability theory.

1660–62 Robert Boyle studies gases.

1666–1704 Sir Isaac Newton actively studies a wide range of natural phenomena.

1669 Danish anatomist and geologist Nicolaus Steno publishes *Prodromus,* the first work to show that fossils are the remains of formerly living organisms, as well as proposing the law of stratal superposition.

1705 Edmund Halley predicts the return of the comet named for him.

1714 Gottfreid Leibniz proposes the conservation of energy.

1736	Carl Linnaeus publishes the first of 12 editions of *Systema naturae,* a book that outlined a system for classification of plants, animals, and minerals.
1736–65	Leonhard Euler studies theoretical mechanics using differential equations.
1738	Daniel Bernoulli investigates the theories of gases and of hydrodynamics.
1743–44	Jean d'Alembert studies energy in Newtonian mechanics and proposes a theory of fluid dynamics.
1751	American scientist Benjamin Franklin discovers that electricity can produce magnetism.
1754	Joseph Black discovers "fixed air" (carbon dioxide).
1772–88	French mathematician and physicist Joseph Lagrange investigates theoretical mechanics and proposes a new formulation of Newtonian mechanics.
1774	Abraham Gottlob Werner publishes his book "On the External Characters of Minerals" as a guide to identify minerals based on their characteristics. Werner also argued that granites crystallized from ocean waters, leading a school of thought called Neptunism.
1770–90	James Hutton pioneers the concept of uniformitarianism, that the natural processes that formed structures in old rocks are the same as the natural processes operating on Earth at present. This is often summarized as the quote "the present is the key to the past."
1776–84	French mathematician and physicist Pierre Laplace applies mathematical methods to theoretical physics, particularly to mechanics and electricity.
1785	James Hutton publishes his *Theory of the Earth,* becoming recognized as the father of modern geology. French physicist Charles Augustin de Coulomb proposes his law of electrostatics. French chemist Antoine Laurent Lavoisier develops the law of conservation of mass and names oxygen.
1790	The French Academy of Sciences establishes the metric system of measurement.
1796	British geologist and surveyor William Smith formulates the principle of fossil succession, laying the foundation for the science of stratigraphy.
1797	British physicists Benjamin Thompson and Benjamin Rumford study the heat generated by work. French chemist Joseph Proust develops the law of definite proportions.
1800	Italian physicist Alessandro Volta develops the electric battery.
1800–02	Jean-Baptiste Lamarck elaborates his theory of evolution based on the inheritance of modified traits.
1801	English physicist Thomas Young demonstrates that light is a wave phenomenon.
1802	French chemist Joseph Louis Gay-Lussac develops his gas law relating pressure and temperature.
1802–05	British chemist John Dalton develops his atomic theory.
1808	French scientist Étienne-Louis Malus discovers and investigates polarized light.
1809	English scientist Sir George Cayley publishes his theoretical studies of aerodynamics, laying the foundation for flight.
1811	Italian scientist Amedeo Avogadro describes gases in molecular terms.
1814	German physicist Joseph von Fraunhofer discovers and investigates optical spectra. French physicist Augustin-Jean Fresnel explains light polarization in terms of light's wave nature.
1818	The first national geologic map is produced, as a map of the United Kingdom by William Smith.
1820	Danish physicist Hans Christian Ørsted and French physicist André-Marie Ampère show that an electric current has a magnetic effect.
1821	English physicist Michael Faraday, who was studying electromagnetism, introduces the concept of magnetic field.
1824	French engineer Nicolas-Léonard-Sadi Carnot publishes his analysis of heat engines, which leads to the laws of thermodynamics.

1827 German physicist Georg Simon Ohm shows the proportionality of electric current and voltage, known as Ohm's law. English botanist Robert Brown discovers the motion of pollen grains suspended in a liquid, called Brownian motion.

1830–33 Charles Lyell publishes his work "Principles of Geology," in which he proposes that geological processes are very slow and the Earth is very old, and emphasizes the uniformitarian concepts of James Hutton.

1831 English physicist Michael Faraday discovers electromagnetic induction, that magnetism can produce electricity. American physicist Joseph Henry invents the electric motor.

1831–36 Charles Darwin collects evidence supporting his theory of evolution while traveling around the globe on the H.M.S. *Beagle*.

1833–60 Adam Sedgwick maps parts of Wales, and proposes divisions of Paleozoic time. He also identifies the origins of many geologic structures, such as folds and faults.

1837 James Dana publishes his "System of Mineralogy."

1840 English physicist James Prescott Joule develops the law of conservation of energy.

1842 Austrian scientist Christian Doppler explains the dependence of the observed frequency on the motion of the source or observer, called the Doppler effect.

1847 German scientist Hermann von Helmholtz expresses the conservation of energy in mathematical terms, the first law of thermodynamics.

1848 English scientist Sir William Thomson (Lord Kelvin) describes absolute zero temperature.

1850 German physicist Rudolf Clausius introduces the concept of entropy, which leads to the second law of thermodynamics. French physicist Jean-Bernard-Léon Foucault measures the speed of light in air, and later in water.

1851 Foucault uses a huge pendulum, known as a Foucault pendulum, to demonstrate the rotation of planet Earth.

1853 British geologist Henry Sorby pioneers the use of the polarizing microscope for petrography and publishes models for the origin of slaty cleavage in rocks.

1854 German mathematician Georg Riemann describes the geometry of curved spaces, applied later by modern physicists to relativity and other problems.

1858 Rudolf Virchow states that cells only arise from other cells. Darwin and Alfred Russel Wallace jointly propose the theory of natural selection.

1859 Charles Darwin publishes *On the Origin of Species by Means of Natural Selection, or the Preservation of Favored Races in the Struggle for Life*. Louis Pasteur disproves the notion of spontaneous generation.

1859 Scottish physicist James Clerk Maxwell develops the kinetic theory of gases, based on a statistical treatment of the gas particles.

1860 The famous debate on evolution by Thomas Henry Huxley and Bishop Samuel Wilberforce takes place at Oxford.

1862 German physicist Gustav Robert Kirchhoff introduces the concept of a blackbody, later study of which leads to the development of quantum mechanics.

1866 Haeckel coins the term *ecology* to mean the study of living organisms and their interactions with the environment and states his famous biogenetic law, that ontogeny recapitulates phylogeny.

1869 Russian physicist Dmitry Mendeleyev develops the periodic table based on atomic mass. American geologist and explorer John Wesley Powell leads a first expedition to the Grand Canyon, providing some of the first geological descriptions of the western United States.

1871 English physicist John William Strutt (Lord Rayleigh) mathematically relates the amount of scattering of light from particles, such as molecules, to the wavelength of the light, thus explaining the color of the sky.

1873 Scottish physicist James Clerk Maxwell presents his set of equations, known as Maxwell's equations, which form a theoretical framework for electromagnetism and predict the existence of electromagnetic waves. Dutch physicist Johannes van der Waals modifies the ideal gas equation to take into account weak attractive intermolecular forces, called van der Waals forces.

1875 Austrian geologist Eduard Suess publishes *Die Entstehung der Alpen,* a milestone paper in understanding the structural geology of the Alps of Europe and in relating his tectonic theories.

1877 English physicist John William Strutt (Lord Rayleigh) publishes his extensive work on acoustics, the science of sound waves. Grove Karl Gilbert publishes a monograph on the Henry Mountains, showing that intrusive plutons can deform host rock.

1879 Austrian physicist Josef Stefan shows experimentally that the rate of energy radiation from a body is proportional to the fourth power of the body's absolute temperature.

1883 Austrian physicist Ludwig Boltzmann explains Stefan's result as a property of blackbodies, known as the Stefan-Boltzmann law. This lays the foundation for the development of quantum mechanics.

1887 German physicist Heinrich Rudolf Hertz observes the photoelectric effect, the emission of electrons from a metal that is irradiated with light, and discovers radio waves. American scientists Albert Abraham Michelson and Edward Williams Morley attempt to measure the motion of Earth in the ether, a proposed medium for the propagation of electromagnetic waves, with a negative result, which leads to the special theory of relativity in the 20th century.

1890 The first monograph of the U.S. Geological Survey is published, by G. K. Gilbert on the origin of glacial Lake Bonneville.

1893 German physicist Wilhelm Wien shows experimentally that the wavelength at which a blackbody radiates at maximal intensity is inversely proportional to the absolute temperature, known as Wien's displacement law.

1895 Scottish geologist Andrew Lawson identifies and names the San Andreas fault and later (in 1908) authors a famous report on the 1906 earthquake. German physicist Wilhelm Conrad Röntgen discovers X-rays.

1896 French physicist Henri Becquerel discovers radioactivity in uranium.

1897 British physicist Sir J. J. Thomson discovers electrons and develops his "plum pudding model" of the atom, where the electrons are imbedded in a positively charged sphere.

1898 French chemist Marie Curie and physicist Pierre Curie isolate radium, which is highly radioactive.

1900 German physicist Max Planck proposes absorption and emission of radiation in discrete amounts, which introduces the quantum concept.

1904 Lord Ernest Rutherford performs the gold foil experiment that demonstrates the existence of the atomic nucleus.

1905 German/Swiss, later American, physicist Albert Einstein publishes his special theory of relativity. To explain the photoelectric effect, Einstein proposes that light consists of photons.

1910–40 Amadeus Grabau publishes a series of 10 books, outlining the stratigraphic and paleontological history of North America, and later China.

1910 Japanese geophysicist Motonori Matuyama recognizes magnetic reversals in Japanese basalts.

1911 Arthur Holmes becomes the first person to use the uranium-lead decay series to date rocks, showing that the Earth is more than a billion years old. Netherlands physicist Heike Kamerlingh Onnes discovers superconductivity. New Zealand–born British physicist Sir Ernest Rutherford discovers the structure of the atom. American physicist Robert A. Millikan uses his "oil drop method" to determine the charge of an electron.

1911–12 Using X-ray methods, British physicists William Henry Bragg and William Lawrence Bragg and German physicist Max von Laue discover the atomic structure of crystals.

1912 Alfred Wegener proposes a theory of continental drift.

1912–35 Victor Goldschmidt authors a series of papers that lay the foundation for modern geochemistry and proposes geochemical models for the composition of the Earth.

1913 Danish physicist Niels Bohr proposes a "planetary model" of the hydrogen atom to explain the hydrogen spectrum, in which the electrons rotate around the nucleus in orbits like planets around the sun. British physicist, Henry Moseley rearranges the periodic table based on atomic number.

1915 Albert Einstein proposes his general theory of relativity.

1916 American physicist Robert Millikan measures the value of the Planck constant, which characterizes all quantum phenomena.

1917 Joseph Grinnell coins the term *ecological niche*.

1919 English astronomer and physicist Arthur Eddington leads an expedition that measures the bending of starlight passing near the Sun during a total solar eclipse, which confirms the general theory of relativity.

1920 Pentti Eskola defines the concept of metamorphic facies.

1922 Soviet mathematician and meteorologist Aleksander Friedmann shows that the general theory of relativity predicts the Universe is expanding.

1923 French physicist Louis de Broglie proposes that matter possesses wave-like properties. American physicist Arthur Holly Compton demonstrates, through the Compton effect, that electromagnetic radiation consists of photons.

1925 German physicist Werner Heisenberg invents a matrix formulation of quantum mechanics. American astronomer Edwin Hubble identifies very distant stars outside the Milky Way Galaxy.

1926 Austrian physicist Erwin Schrödinger publishes his formulation of quantum mechanics in the form of the Schrödinger equation.

1927 Werner Heisenberg proposes his uncertainty principle. American physicists Clinton Davisson and Lester Germer show that electrons possess wave-like properties. Leading to the big bang theory, Belgian astronomer Georges Lemaître states that the universe began its expansion from a tiny, hot state.

1928 British geologist Arthur Holmes proposes that radioactive decay causes thermal convection in Earth's mantle and that this convection causes the continents to drift. British physicist Paul Dirac derives the Dirac equation, which predicts the existence of antiparticles.

1929 American astronomer Edwin Hubble demonstrates that all galaxies are receding from each other, indicating the expansion of the universe. Alexander du Toit begins to publish observations correlating fossils between South America and Africa in support of continental drift.

1931 Ernst Ruska and Max Knoll make the first electron microscope.

1932 Indian-born American astrophysicist Subrahmanyan Chandrasekhar proposes that when a sufficiently massive star reaches the end of its life, it will collapse to a black hole. American physicists Ernest O. Lawrence and M. Stanley Livingston invent the cyclotron, a particle accelerator for investigating nuclei and elementary particles. American physicist Carl D. Anderson discovers the positron, the electron's antiparticle. British physicist James Chadwick discovers the neutron.

1933 Swiss astronomer Fritz Zwicky studies the rotation of galaxies and shows that they must contain more mass than is visible, introducing the idea of dark matter. Georges Lemaître proposes the theory of the big bang, initially criticized as being too much like creationist accounts, but later endorsed by Albert Einstein.

1934 French physicists Irème Joliot-Curie and Frédéric Joliot-Curie produce the first artificial radioactive isotopes.

1935 Japanese physicist Hideki Yukawa proposes the theory of the nuclear force, binding protons and neutrons into nuclei, which predicts the existence of mesons.

1936 Hans Stille publishes his models for the tectonic pulses of Europe, correlating different events across Europe, Asia, and eventually the globe.

1937 Normal Levi Bowen proposes models of magmatic differentiation by partial melting and by fractional crystallization. American physicists Carl D. Anderson and Seth Neddermeyer discover the muon in cosmic rays.

1938 Soviet physicist Pyotr Kapitsa discovers that liquid helium exhibits superfluidity near 0 K. American physicist Hans Bethe explains the source of energy production in stars as nuclear fusion reactions.

1938–39 Austrian physicists Lise Meitner and Otto Frisch explain that the German chemists Otto Hahn and Fritz Strassmann achieved nuclear fission by bombarding uranium with neutrons.

1939 Linus Pauling publishes *The Nature of the Chemical Bond and the Structure of Molecules and Crystals: An Introduction to Modern Structural Chemistry*.

1941 Milutin Milankovitch publishes his model that changes in the orbital parameters of Earth change the amount of incoming solar radiation, leading to climate cycles on Earth, preserved as Milankovitch cycles in the rock record.

1942 A team led by Italian/American physicist Enrico Fermi produces the first controlled nuclear fission chain reaction. The United States initiates the Manhattan Project to construct a nuclear fission (atomic) bomb.

1943 As part of the Manhattan Project, the Los Alamos laboratory is built in New Mexico, directed by American physicist Robert Oppenheimer.

1945 Erwin Schrödinger publishes *What Is Life*, a book that inspires many biologists.

1946 American chemist Willard Frank Libby invents the carbon 14–dating technique for determining when living organisms died. The first programmable digital computer, the Electronic Numerical Integrator and Comparator (ENIAC) starts operation.

1947 A team directed by British astronomer Bernard Lovell completes construction of the first radio telescope. British physicist Cecil Frank Powell discovers the pion, predicted by Yukawa in 1935. American physicists John Bardeen, William Shockley, and Walter Brattain invent the transistor, a semiconductor device.

1948 George Gamow publishes a big bang model for the origin of the universe and predicts the presence of cosmic background radiation and the origin of the chemical elements.

1949 German-American physicist Maria Goeppert Mayer and German physicist Hans Jensen model the nucleus of atoms as consisting of shells of protons and neutrons. American geologist Francis Pettijohn publishes his book *Sedimentary Rocks*, which laid the foundation for modern sedimentology.

1950 Swedish astrophysicist Hannes Alfvén reaches an understanding of the physics of plasmas (ionized gases), with relevance to space science and, later, to nuclear fusion. The United States Congress creates the National Science Foundation for the funding of basic research and science education.

1951–52 American physicists Harold Ewen and Edward Mills Purcell observe the 21-cm radio signal from hydrogen atoms in space.

1954 American seismologist Hugo Benioff recognizes that earthquakes beneath island arcs are concentrated in narrow zones and suggests that the arcs are being thrust over sinking oceanic crust, a forerunner to the modern subduction zone model.

1956 American physicists Clyde Cowan, Frederick Reines, F. B. Harrison, H. W. Kruse, and A. D. McGuire discover the electron neutrino.

1956–57 Chinese-American physicist Chien-Shiung Wu experimentally confirms the proposal by the Chinese-American physicists Tsung-Dao Lee and Chen Ning Yang that the weak force might not obey reflection symmetry.

1957 American physicists John Bardeen, Leon Cooper, and Robert Schrieffer propose an explanation for superconductivity in terms of conduction by electron pairs. Bayer and General Electric develop polycarbonate plastics.

1958 Japanese physicist Leo Esaki invents the tunnel diode, which exploits quantum tunneling.

1959 Israeli physicist Yakir Aharonov and American physicist David Bohm predict that magnetic fields can affect particles in an observable, nonclassical way when the particles do not pass through the field. Austrian molecular biologist Max Perutz determines the structure of hemoglobin.

1960 Robert Dietz and Harry Hess propose the concept of seafloor spreading. The Aharonov-Bohm effect is observed. American physicist Theodore Maiman constructs the first laser from a ruby crystal.

1962 American physicists Leon M. Lederman, Melvin Schwartz, and Jack Steinberger discover the muon neutrino. Rachel Carson publishes *Silent Spring,* a book that stimulates the environmental movement.

1963 Dutch-American astronomer Maarten Schmidt discovers the first quasar (QUASi-stellAR radio source), a very distant object that appears similar to a star but radiates more than some galaxies.

1964 American physicists Murray Gell-Mann and George Zweig independently propose the existence of quarks as components of protons, neutrons, and other hadrons.

1965 American physicists Arno Penzias and Robert Wilson discover the cosmic microwave background. Canadian geologist J. Tuzo Wilson publishes “A New Class of Faults and Their Bearing on Continental Drift” in *Nature,* a paper widely held to be the start of the plate tectonic paradigm. Cambridge Instruments makes the first commercial scanning electron microscope.

1967 American physicists Steven Weinberg and Sheldon Glashow and Pakistani physicist Abdus Salam independently propose unifying the electromagnetic and weak forces to a single, electroweak force.

1967–68 British astronomers Jocelyn Bell and Anthony Hewish discover that certain stars, called pulsars, emit periodic radio pulses. American astrophysicist Thomas Gold explains pulsars as rotating neutron stars.

1969 A group of American physicists, including Jerome I. Friedman, Henry Kendall, and Richard E. Taylor, discover experimental evidence for the existence of quarks inside protons.

1970 John Dewey and John Bird apply the concept of plate tectonics to the ancient Appalachian mountain belt.

1970–73 Physicists develop the “standard model” of elementary particles, which includes the strong and electroweak forces.

1972 NASA launches the first Landsat satellite. Preston Cloud proposes models for the evolution of organisms and relationships between life, atmospheric chemistry, and geology for the early Earth.

1972 Stephen Jay Gould and Niles Eldridge propose the theory of punctuated equilibrium as a method for evolutionary events.

1974 English physicist Stephen Hawking proposes that black holes can radiate particles and eventually evaporate. American physicists Burton Richter and Samuel C. C. Ting and their groups independently discover the charm quark.

1974–77 American physicist Martin L. Perl and colleagues discover the tau particle.

1975–77	Polish-American mathematician Benoit B. Mandelbrot introduces the concept of fractals, patterns in systems that are similar to themselves at all scales.
1977	Robert Ballard and his team discover chemosynthetic communities surrounding hydrothermal vents. Carl Woese proposes a third domain of life, Archaea. American physicist Leon Lederman and colleagues discover the bottom quark.
1978	American astronomer Vera Rubin and others conclude from an analysis of the rotation of galaxies that the gravity from the visible stars is insufficient to keep them from flying apart, and they must contain invisible matter, called dark matter.
1979	French physicist Pierre-Gelles de Gennes publishes his work on the theories of polymers and liquid crystals.
1980	American physicist Alan Guth proposes adding inflation—a very brief period of extremely rapid expansion of the universe—to the big bang theory, in order to better explain observations.
1981	German physicist Gerd Binnig and Swiss physicist Heinrich Rohrer invent the scanning tunneling microscope, which can image surfaces to the detail of individual atoms.
1983	A team led by the Italian physicist Carlo Rubbia discovers the W and Z bosons, the carriers of the weak force.
1985	English chemist Sir Harry Kroto and American chemists Richard Smalley and Bob Curl discover the structure of the buckminsterfullerene molecule.
1986	Swiss physicist Karl Alexander Müller and German physicist Johannes Georg Bednorz discover high-temperature superconductors, materials that become superconducting at temperatures much farther above 0 K than were previously known.
1989	American astronomers Margaret Geller and John Huchra discover that the galaxies in the universe are located on thin sheets surrounding great voids that are empty of galaxies.
1989–92	The U.S. National Aeronautics and Space Administration (NASA) launches the Cosmic Background Explorer (COBE) satellite, which maps the radiation from the sky in all directions, the cosmic microwave background, a remnant from the big bang. The cosmic microwave background is found to be very uniform and to correspond to the radiation of a blackbody at a temperature of 2.725 K. Tiny angular fluctuations in the radiation's generally uniform distribution are detected, reflecting on some nonuniformity in the universe at a very early age.
1990	NASA launches the *Hubble Space Telescope* as a satellite above Earth's atmosphere to study the universe at high resolution.
1993	The U.S. Air Force completes the Global Positioning System (GPS), allowing users on Earth to locate themselves and navigate around the world.
1994	The top quark is discovered at Fermilab. Hubble telescope.
1995	American physicists Eric Cornell and Carl Wieman produce a Bose-Einstein condensate of 2,000 atoms at a temperature lower than 10^{-6} K, thus confirming a prediction of Bose-Einstein statistics. American geophysicists Xiaodong Song and Paul Richards demonstrate that Earth's solid inner core, with a diameter of 1,500 miles (2,400 km), rotates a little faster than the rest of the planet. The top quark is discovered by a group at Fermilab. Anti-hydrogen atoms, consisting of an antiproton and a positron, are created at the European Organization for Nuclear Research (CERN).
1998	Observations of supernovas indicate that the expansion of the universe is accelerating.
2000	A collaboration at Fermilab announces the detection of the tau neutrino.
2001	The first complete Archean ophiolite is discovered in China by American geologist T. Kusky and Chinese geologist J. H. Li.

2003 The Human Genome project, a collaborative group of scientists from many nations, complete the sequence of the human genome.

2006 President George W. Bush announces the Advanced Energy Initiative (AEI) to increase research on technology to reduce oil use for transportation, including hybrid-vehicle batteries, ethanol, and hydrogen–fuel cell vehicles and fueling stations. AEI also supports research into electricity production from clean coal, wind, and solar power.

2008 The U.S. Senate introduces *The Green Chemistry Research and Development Act of 2008* for the advancement of research into environmentally friendly chemicals by the National Science Foundation (NSF), National Institute of Standards and Technology (NIST), Environmental Protection Agency (EPA), and Department of Energy.

APPENDIX II
GLOSSARY

abrasion a process that occurs when particles of sand and other sizes are blown by the wind and impact each other

absorption in physics and astronomy, the process where energy from a photon is taken up by matter, typically electrons of an atom, and converted into some other form of energy (typically heat), causing reduction of light from a distant source. An absorption line is a dark line in an otherwise continuous spectrum, where the light from one narrow frequency range has been removed by some process, typically interaction with interstellar medium.

abyssal plains stable, flat parts of the deep oceanic floor, typically covered with fine-grained sedimentary deposits called deep sea oozes, derived from the small skeletons of siliceous organisms that fell to the seafloor

accreted terranes coherent regional-scale blocks of rocks with distinctive stratigraphic and structural histories that have been added to the edges of continents at convergent plate margins

accretion the transfer of material, such as sedimentary rocks, from an oceanic plate to an overriding continental plate at a convergent plate margin. Less commonly, the term may be applied to the addition of magma that crystallizes into rocks and is added to the extensional plate boundaries in mid-ocean ridges. The term can also be applied to the gravitational accumulation of dust, gas, and rocky bodies such as asteroids to a larger body such as a planet.

accretionary beaches wide summer beaches characterized by the movement of sediment from offshore to onshore

accretionary prism, accretionary wedge a structurally complex belt of rocks formed just above a subduction zone, characterized by strongly folded and faulted rocks scraped off from the downgoing oceanic plate

accretion disk a diffuse collection of material in orbit around a central celestial body

achondrite a stony meteorite that does not contain chondrules

acid rain rain or other forms of precipitation that have acidic components leading to a pH of less than 7. The extra acidity in acid rain comes from the reaction of air pollutants, mostly sulfur and nitrogen oxides, with water to form strong acids such as sulfuric and nitric acid

aerosol microscopic droplets or airborne particles that remain in the atmosphere for at least several hours

age elements elements that tend to accumulate in tissues as the tissues get older

aggradation the deposition of sediments along a river bed, causing the bed to rise

aggrading barriers barrier beaches that are growing upward in place as sea levels rise

alluvial fans coarse-grained deposits of alluvium that accumulate at the fronts of mountain canyons

Amors asteroids that orbit between Earth and Mars but do not cross Earth's orbit

amphibolite a metamorphic rock consisting mainly of minerals of the amphibole group such as hornblende, typically derived from a mafic igneous rock

amplification a process of transferring energy along the wave crest as the waves are forced to become shorter lengthwise, causing the wave height to increase

amplitude one-half of the wave height in a wave train, measured from the bottom of the trough to the top of the crest

andesite an intermediate composition, dark, fine-grained volcanic rock consisting mostly of plagioclase feldspar, with lesser amounts of biotite and hornblende. It is the extrusive equivalent of diorite and found mostly in continental margin magmatic arcs.

Andes Mountains a 5,000-mile- (8,000-km-) long mountain range in western South America, running generally parallel to the coast, between the

Caribbean coast of Venezuela in the north and Tierra del Fuego in the south

angle of repose the steepest angle at which a loose material such as sand, gravel, or boulders can be stacked

angular velocity a measure in degrees of the change in angle per unit time as an object spins about a pivot point. If an object is rotated about a pivot point, the angular velocity stays the same with increasing distance from the pivot point, but the linear velocity (speed) will increase with distance from the pivot point.

anorogenic granite a granite that intrudes a continental area at a time not associated with an orogeny or convergent margin tectonism, typically in the middle parts of supercontinents; may signal heating from below by mantle upwelling and thermal insulation by the large continent

antecedent stream a stream that has maintained its course across topography that is being uplifted by tectonic forces; these cross high ridges

anthropogenic an adjective used to describe changes caused by humans

anticline a fold in which the beds dip outward and the older rocks are in the center of the fold structure

anticlinorium a large regional scale anticline that may have smaller-scale anticlines and synclines superimposed on the larger-scale structure

antimatter the counterpart of matter, made of antiparticles the same way that matter is made of particles

antiparticle most kinds of particles have an associated antiparticle that has the same mass and opposite charge as the particle. For instance, electrons are associated with their antiparticle counterparts, the positrons.

aphelion the point in an orbit that is farthest from the Sun

Apollo asteroids asteroids that orbit less than one astronomical unit from the sun with periods longer than one year

aquicludes rock or soil units that stop the movement of water

aquifer any body of permeable rock or regolith saturated with water through which groundwater moves

aquitard rock or soil units that restrict the flow of water

Archaea a domain of life consisting of simple organisms that appeared on Earth by 3.85 billion years ago

Archean the oldest eon of geological time, ranging from 4.5 billion years ago until 2.5 billion years ago

arête a sharp-edged ridge that forms where two cirques intersect in a mountain range

argillite a clay-rich, fine-grained sedimentary rock

artesian pressure (also, artesian spring, artesian system) a permeable layer, typically a sandstone, that is confined between two impermeable beds, creating a confined aquifer. In these systems, water enters the system only in a small recharge area, and if this is in the mountains, then the aquifer may be under considerable pressure. This is known as an artesian system.

assimilation in geology, the process whereby a crystal or piece of rock is incorporated into an igneous melt, and its chemical constituents become part of the melt

asteroid a rocky or metallic body in space orbiting the Sun

asteroid belt area of the solar system between the orbits of Mars and Jupiter that contains millions of asteroids

asthenosphere weak, partially molten layer in the Earth beneath the lithosphere, extending to about 155 miles (250 km) depth. The lithosphere slides on top of this weak layer, enabling plate tectonics to happen.

astronomical unit (AU) the distance from the Sun to the Earth, or 93 million miles (150 million km)

astronomy the study of celestial objects and phenomena that originate outside the Earth's atmosphere

astrophysics the branch of astronomy that examines the behavior, physical properties, and dynamic processes of celestial objects and phenomena

Aten asteroids asteroids that orbit at less than one astronomical unit from the sun and have an orbital period of less than one year. Some of these cross Earth's orbit.

atmosphere the envelope of air that surrounds the Earth, held in place by gravity. The most abundant gas in the atmosphere is nitrogen (78 percent), followed by oxygen (21 percent), argon (0.9 percent), carbon dioxide (0.036 percent), and minor amounts of helium, krypton, neon, and xenon.

atmospheric pressure the force per unit area (similar to weight) that the air above a certain point exerts on any object below it

atolls geological structures that form circular, elliptical, or semicircular shaped islands made of coral reefs that rise from deep water. Atolls surround central lagoons, typically with no internal landmass

auriferous gold-bearing

aurora glowing arches or streamers of light sometimes visible in high latitudes around both the North and South Poles. Auroras are formed by interaction of the solar wind with the Earth's magnetic field.

avalanche a moving mixture of rock, soil, or regolith that moves rapidly, perhaps by riding on a cushion of air trapped as the material fell off a nearby mountain

avulsion the process by which a river breaks through a river levee and flows onto the floodplain

back arc the part of a magmatic arc that is on the continent side of an arc, or on the side furthest from the trench; includes back arc basins

backshore the area extending from the top of the beach ridge in the foreshore to the next feature (dune, seawall, forest, lagoon) closer to the mainland

banded-iron formation a distinctive type of sedimentary rock consisting of thin layers of iron oxides (typically magnetite or hematite) alternating with layers of iron-poor shale or chert. Banded-iron formations are common in some Precambrian rock sequences.

barrier islands narrow, linear, mobile strips of sand that are up to about 30–50 feet (10–15 m) above sea level and typically form chains located a few to tens of miles offshore along many passive margins. They are separated from the mainland by the back-barrier region, which is typically occupied by lagoons, shallow bays, estuaries, or marshes.

barrier spits narrow ridges of sand attached to the mainland at one end and terminating in a bay or the open ocean on the other end

basalt the most common igneous rock of the oceanic crust. Its subvolcanic or plutonic equivalent is called gabbro. The density of basalt is 3.0 g/cm^3; its mineralogy includes plagioclase, clinopyroxene, and olivine.

basin, sedimentary basin a depression in the surface of the Earth or other celestial body is known as a basin. When this depression becomes filled with sediments, it is known as a sedimentary basin.

bayhead delta a delta deposited by a river in a bay or estuary, not in the open ocean

beach accumulations of sediment exposed to wave action along a coastline

beachface the side of a coast or barrier island facing the open ocean

bed load the coarse particles that move along or close to the bottom of the stream bed

bench a flat bedrock platform that borders many coastal cliffs, formed by erosion or beveling by waves

Benioff zone a narrow zone of earthquakes along a convergent boundary that marks the plane of slip between a subducting plate and an overriding plate, named after its discoverer, Hugo Benioff

benthic, benthos an environment that includes the ocean floor. Benthos are those organisms that dwell on or near the seafloor.

berm a small ridge and change in slope at the top of the foreshore

big bang theory a theory explaining the origin of the universe, in which the universe originated 10–20 billion years ago in a single explosive event during which the entire universe suddenly exploded out of nothing, reaching a pea-sized supercondensed state with a temperature of 10 billion million million degrees Celsius in (10^{-36}) of a second after the big bang

binary star systems two stars that rotate in orbit around each other

biofuels fuels such as methane that are produced from renewable biological resources including recently living organisms, such as plants, and their metabolic byproducts, such as manure

biological weathering the breaking down of rocks and minerals by biological agents such as roots, burrowing organisms, and bacteria

biome a climatically and biologically defined area with a distinctive community of plants, animals, and soil organisms

biosphere collection of all living organisms on the Earth and the environments in which they live

biostratigraphy the branch of stratigraphy that uses fossil assemblages and index fossils to correlate and assign relative ages to strata

bioturbation the process by which organisms burrow and dig into soft sediment and destroy fine-scale layering

blackbody a body that absorbs all radiation that falls on it when it is cold and emits at all wavelengths as it is progressively heated

black hole a super dense collection of matter that has collapsed from a giant star or stars and has such a strong gravity field that nothing can escape from it, not even light

black smoker chimneys hydrothermal vent systems that typically form near active magmatic systems along the mid-ocean ridge system, approximately two miles (3 km) below sea level. Black smokers form by seawater percolating into fractures in the seafloor rocks near the active spreading ridge, where the water gets heated to several hundred degrees Celsius. This hot pressurized water leaches minerals from the oceanic crust and extracts other elements from the nearby magma. The superheated water and brines then rise above the magma chamber in a hydrothermal circulation system and escape at vents on the seafloor, forming the black smoker hydrothermal vents.

blazar a very dense and variable source of energy associated with supermassive black holes at the center of a galaxy

body waves seismic waves that travel through the whole body of the Earth and move faster than surface waves. Body waves are of two types—P, or compressional waves, and S, for shear or secondary waves. P-waves or compressional waves deform material through a change in volume and density, and these can pass through solids, liquids and gases. The kind of movement associated with passage of a P-wave is a back and forth type of motion. S or secondary waves change the shape of a material but not its volume. Only solids can transmit shear waves, whereas liquids can not. Shear waves move material at right angles to the direction of wave travel, and thus they consist of an alternating series of sideways motions.

bolide a name for any unidentified object entering the planet's atmosphere

bore a wave that forms in some bays and estuaries, where the shape of the coastline tends to funnel water from the rising tides into narrower and narrower places, causing the water to pile up. When this happens, the volume of water entering the bay forms a wave called a tidal bore that moves inland, typically growing in height and forward velocity as the bay becomes narrower and narrower.

boudin a sausage-shaped lozenge of hard rock enclosed in a matrix of softer rock, typically occurring as a string or train of similar boudins. They form by a hard layer's being pulled apart into small sausage-shaped blocks during deformation, indicating extension parallel to the train of boudins

brachiopod a two-shelled marine invertebrate organism

brackish a term used to describe water that is mixed in salt content between salty and fresh

braid bars gravel and sand bars that separate the interconnected channels in a braided stream

breccia a fragmented rock produced by the breaking of preexisting rocks

bryozoans colonial organisms with hard skeletons of calcium carbonate, resembling coral

calc-alkaline a rock series, typically including basalt, andesite, dacite, and rhyolite, in which calcium oxide (CaO) generally declines with increasing silicon dioxide (SiO_2). The calc-alkaline rock series is typical of that found in island arc settings.

calcium-aluminum inclusions a group of very high-temperature minerals found inside some chondrules, typically exhibiting textures like concentric skins of an onion

caldera a roughly circular or elliptical depression, often occupied by a lake, that forms when the rocks above a subterranean magma mass collapse into the magma during a cataclysmic eruption

calving the process whereby large blocks of ice plunge off the front of a tidewater glacier and fall into the sea, making icebergs

Cambrian the first geologic period of the Paleozoic era and the Phanerozoic eon. The Cambrian began 544 million years ago and ended 505 million years ago

capacity in hydrology, the potential load a stream can carry, measured in the amount (volume) of sediment passing a given point in a set amount of time

carbonaceous chondrites chondritic meteorites that contain organic material, such as hydrocarbons in rings and chains, and amino acids

carbonate a sediment or sedimentary rock containing the carbonate (CO_3^{2-}) ion. Typical carbonates include limestone and dolostone.

carbonatite an intrusive or extrusive igneous rock that has more than 50 percent carbonate minerals. Many carbonatites resemble marble in appearance, but are igneous in origin. Most carbonatites are associated with continental rift settings.

carbon cycle a complex series of processes where the element carbon makes a continuous and complex exchange between the atmosphere, hydrosphere, lithosphere and solid Earth, and biosphere

Carboniferous a late Paleozoic geologic period in which the Carboniferous system of rocks was deposited, between 360 and 286 million years ago

carbon sequestration a group of processes that enable long-term storage of carbon in the terrestrial biosphere, in the oceans, or deep underground, effectively isolating that carbon from the atmosphere

cave systems, caves underground openings or passageways in rock that are larger than individual spaces between the constituent grains of the rock. The term is often reserved for spaces that are large enough for people to enter, whereas other definitions reserve the term to describe any rock shelter, including overhanging cliffs.

cavitation a process that occurs when a stream's velocity is so high that the vapor pressure of water is exceeded and bubbles begin to form on rigid surfaces. These bubbles alternately form and then collapse with tremendous pressure, and they act as an extremely effective erosive agent

Cenozoic the most recent era of geologic time, marking the emergence of the modern Earth, starting at 66 million years ago and continuing until the present

Centaurs a group of asteroids that have highly eccentric orbits that extend beyond yet cross the orbits of Jupiter and Saturn, thus can potentially collide with these planets

centrifugal force a force, related to the spinning of the planet, that acts perpendicular to the axis of rotation of the Earth and affects the tides

charnockite an orthopyroxene-bearing granite consisting of quartz, perthite, and orthopyroxene, found in many high-grade Precambrian metamorphic terranes

chemical weathering decomposition of rocks through the alteration of individual mineral grains

chert a fine-grained almost glassy siliceous chemical sedimentary rock. Many cherts are made from the siliceous tests or outer skeletons of small organisms called radiolarians. Other chert is derived from volcanic activity, and still other is derived by chemical precipitation from seawater.

chlorofluorocarbons (CFCs) a group of inert, nontoxic, and easily liquefied chemicals that were once widely used in refrigeration. When released to the atmosphere they become long-lived greenhouse gases that contain carbon, hydrogen, fluorine, and chlorine, increasing in atmospheric concentration as a result of human activity. Chlorofluorocarbons are thought to cause depletion of the atmospheric ozone layer.

chondrite a stony meteorite containing chondrules

chondrules small lumps in chondritic meteorites, thought to represent melt droplets that formed before the meteorite fragments were accreted to asteroids, thus representing some of the oldest material in the solar system

chromite an iron-magnesium oxide mineral belonging to the spinel group and typically found in mantle peridotite and in some layered igneous intrusions

chromosphere the lower part of the solar atmosphere, resting directly above the photosphere

cirques bowl-shaped hollows that open downstream and are bounded upstream by a steep wall

clastic rocks composed of fragments, or clasts, of preexisting rock

cleavage in minerals, the way certain minerals break along specific crystallographic directions; in structural geology, where the preferred alignment of phyllosilicate minerals causes parallel planes of weakness to develop in a rock

climate the average weather of a place or region

climate change the phenomenon characterized by change in global temperatures, patterns of precipitation, wind, and ocean currents in response to human and natural causes

clouds visible masses of water droplets or ice crystals suspended in the lower atmosphere, generally confined to the troposphere

coastal plain relatively flat area along the coast, that was formerly below sea level during past high sea-level stand

coastal zone the region on the land that is influenced in some way by humidity, tides, winds, salinity, or biota from the sea. A more restrictive definition is the area between the highest point that tides influence the land and the point at which the first breakers form offshore.

collision zone a zone of uplifted mountains where two continental plates or magmatic arcs have collided as a result of subduction along a convergent plate boundary

coma the gaseous rim of a comet, from which the tail extends

comet an icy or mixed icy and rocky body that orbits the Sun and typically emits a long tail on its close approach to the Sun

compaction a phenomenon in which the pore spaces of a material are gradually reduced, condensing the material and causing the surface to subside

competence the maximum size of particles that can be entrained and transported by a stream under a given set of hydraulic conditions, measured in diameter of largest bed load

compressional waves *See* body waves.

conodonts extinct chordate, toothlike fossils that were part of a larger organism of the class Conodonta

consequent stream a stream whose course is determined by the direction of the slope of the land

constellation human groupings of stars in the sky into patterns, even though they may be far apart and lined up only visibly, and not close at all in space

continental crust the rock material that makes up the continents of the planet, extending to about 20 miles (35 km) depth and covering about 34.7 percent of the Earth's surface. Continental crust includes a wide variety of rock types and ages of rocks, but in general, the crust has an average composition of granodiorite.

continental drift a theory that was a precursor to plate tectonics, stating that the continents are relatively light objects that are floating and moving freely across a substratum of oceanic crust

continental margin the transition zone between thick buoyant continental crust and the thin dense submerged oceanic crust

continental shelf a submarine plain that forms the border of a continent, underlain by continental crust and having shallow water. Sedimentary deposits on continental shelves include muds, sands, and carbonates.

convection and the Earth's mantle a description of the main heat transfer mechanism in the Earth's mantle. Convection is a thermally driven process where heating at depth causes material to expand and become less dense, causing it to rise while being replaced by complementary cool material that sinks.

convergent boundaries places where two plates move toward each other, resulting in one plate sliding beneath the other when a dense oceanic plate is involved, or collision and deformation when continental plates are involved. These types of plate boundaries may experience the largest of all earthquakes.

coral invertebrate marine fossils of the phylum Cnidaria characterized by radial symmetry and a lack of cells organized into organs. They are related to jellyfish, hydroids, and sea anemones, all of which possess stinging cells. Corals are the best preserved of this phylum because they secrete a hard calcareous skeleton that typically forms hard reefs and gets preserved in the geological record.

Coriolis effect an apparent deflection of a freely moving body toward the right in the northern hemisphere and toward the left in the southern hemisphere

Coriolis force an apparent force that arises because the surface of the Earth at the equator is rotating through space faster than points on and near the poles. When water or air moves toward the pole it is moving faster than the new solid ground beneath it, causing objects to be deflected to the right in the northern hemisphere, and to the left in the southern hemisphere.

corrosiveness in soil, a measure of the ability to corrode or chemically decompose buried objects, such as pipes, wires, tanks, and posts

cosmic background radiation faint electromagnetic radiation that fills the universe, discovered in 1965, radiating as a thermal blackbody at 2.75 Kelvin. It is thought to be a remnant of the big bang.

cosmic rays extremely energetic particles that move through space at close to the speed of light. Most cosmic rays are made of atomic nuclei, about 90 percent of which are bare hydrogen nuclei (protons), 9 percent are helium nuclei (alpha particles), and about 1 percent are electrons (beta minus particles), but cosmic rays include a whole range of particles that spans the entire periodic table of the elements.

cosmology the study of the structure and evolution of the universe

covalent bond a type of chemical bonding characterized by the sharing of electrons between two or more atoms

cratons very old and stable portions of the continents that have been inactive for billions of years and typically have subdued topography including gentle arches and basins

creep the barely noticeable slow downslope flowing movement of regolith involving the slow plastic deformation of the regolith, as well as repeated microfracturing of bedrock at nearly imperceptible rates

Cretaceous the youngest of three periods of the Mesozoic, during which rocks of the Cretaceous system were deposited. The Cretaceous ranges from 144 million years ago (Ma) until 66.4 Ma and is divided into the Early and Late epochs and 12 ages.

cryosphere the portion of the planet where temperatures are so low that water exists primarily in the frozen state

crystal lattice the orderly, regular, and symmetric three-dimensional arrangement of atoms in a crystal

cumulates igneous rocks that form by the accumulation of crystals in a magma chamber, either from settling to the bottom and sides of the chamber, or floating to the top

cyclone a tropical storm equivalent to a hurricane, that forms in the Indian Ocean

dacite intermediate composition volcanic rock with high iron content, having a composition between andesite and rhyolite

dark matter a hypothetical form of matter of unknown composition but probably consisting of elemental particles. Because dark matter does not emit or reflect electromagnetic radiation, it can be detected only by observing its gravitational effects

debris avalanche a granular flow that moves at high velocity and covers large distances

debris flow the downslope movement of unconsolidated regolith, most of which is coarser than sand and typically chaotically mixed between fragments of different sizes. Some debris flows begin as slumps, but then continue to flow downhill as debris flows. They typically fan out and come to rest when they emerge out of steeply sloping mountain valleys onto lower-sloping plains.

decadal varying on scale of a decade, or 10-year time frame

deflation a process whereby wind picks up and removes material from an area, resulting in a reduction in the land surface

deformation of rocks a term, often used informally, to describe structural and geometric changes to rocks or rock masses. Deformation of rocks is measured by three components: strain, rotation, and translation. Strain measures the change in shape and size of a rock, rotation measures the change in orientation of a reference frame in the rock, and translation measures how far the reference frame has moved between the initial and final states of deformation.

delta low, flat deposits of alluvium at the mouths of streams and rivers that form broad triangular or irregular shaped areas that extend into bays, oceans, or lakes. They are typically crossed by many distributaries from the main river and may extend for a considerable distance underwater.

delta front an extremely sensitive environment located on the seaward edge of the delta. It is strongly affected by waves, tides, changing sea level, and changes to the flux or amount of sediment delivered to the delta front. Many delta fronts have an offshore sandbar known as a distributary mouth bar, or barrier island system, parallel to the coast along the delta front.

delta plain a coastal extension of the river system composed of river and overbank sedimentary deposits, in a flat meandering stream type of setting. These environments are at or near (or in some cases below) sea level, and it is essential that the overbank regions receive repeated deposits of muds and silts during flood stages to continuously build up the land surface as the entire delta subsides below sea level by tectonic processes.

dendritic drainage randomly branching stream patterns that form on horizontal strata or on rocks with uniform erosional resistance

depositional coast a coastline that is dominated by depositional landforms such as deltas or broad carbonate platforms

desalination any number of individual processes that remove salt from water and make it potable, or fit for drinking

desert an area characterized by receiving less than 1 inch (2.5 cm) of rain each year over an extended period of time

desertification the conversion of previously productive lands to desert

desert pavement a long-term stable surface in deserts characterized by pebbles concentrated along the surface layer

Devonian the fourth geological period in the Paleozoic era, spanning the interval from 408 to 360 million years ago

dextral a term used to describe the sense of motion along a fault where the block on the opposite side of the fault moves to the right

diagenesis a group of physical and chemical processes that affects sediments after they are deposited but before they undergo deformation and metamorphism

diamictite a poorly or nonsorted conglomerate containing a wide variety of rock fragments. Diamictites can be produced from glacial ice sheets, volcanic lahars, or debris flows, or by tectonic and erosional processes

diapir an igneous intrusion emplaced by buoyancy forces and differential pressure between the magma and surrounding country rock, and by the heat energy transferred from the magma to the country rock

diatreme a breccia-filled volcanic pipe formed by a gaseous explosion

differentiation in geology, the separation of one composition crystal or liquid from another, by processes that may include melting, crystallization, and removal of the phase from other parts of the system

diffraction a process that occurs when energy moves or is leaked sideways along a wave crest, enabling the wave to grow along the wave front to fill the available area inside a wide bay that the wave has entered through a narrow opening

dike any tabular, parallel-sided igneous intrusion that generally cuts across layering in the surrounding country rocks

dilation expansion of a rock caused by the development of numerous minor cracks or fractures in the rocks that form in response to the stresses concentrated along the fault zone

diorite gray-colored intermediate composition intrusive igneous rock composed of plagioclase feldspar, biotite, hornblende, and rarely pyroxene, small amounts of quartz, and other accessory minerals

dirty ice cometary ice that is mixed with dust or other material

discharge the amount of water moving past a point in a stream, usually measured in cubic feet or cubic meters per second

discharge areas the point where water leaves the groundwater system

dislocation a crystallographic defect in a crystal lattice, typically an extra row or wall of atoms, or a twisted misarrangement of the atomic structure

dispersion a process that moves energy from the initially high wave crest sideways, and in doing so takes energy away from the central area, decreasing the height of the wave

dissolution the process in which water reacts chemically with rocks and carries elements away in solution, gradually dissolving the rock. This often results in the formation of caves and other karst features, and it may result in underground collapse and sinking of the land.

dissolved load dissolved chemicals, such as bicarbonate, calcium, sulfate, chloride, sodium, magnesium, and potassium. The dissolved load tends to be high in streams fed by groundwater.

divergent boundaries places where two plates move apart, creating a void that is typically filled by new oceanic crust that wells up to fill the progressively opening hole; also called divergent margins

Doppler shift a shift in the frequency and wavelength of a wave for an observer moving relative to the source of the waves

downslope flow movement of a sediment/water/rock mixture downhill

drainage basin the total area that contributes water to a stream. The line that divides different drainage basins is known as a divide

drawdown the rapid retreat of water from a coastline immediately before a tsunami hits. The drawdown may resemble a rapidly retreating tide.

dropstones isolated pebbles or boulders in marine sediments, deposited when rocks trapped in floating icebergs melted out of the ice and dropped to seafloor

drought a period when the yearly rainfall for a region is significantly less than normal

drumlins teardrop-shaped accumulations of till that are up to about 150 feet (50 m) in height, and tend to occur in groups. These have a steep side that faces in the direction from which the glacier advanced and a back side with a more gentle slope. Drumlins are thought to form beneath ice sheets and record the direction of movement of the glacier.

dune low, wind-blown mounds of sand or granular material, with variable size and shape depending on sand supply, vegetation, and wind strength

dunite a plutonic igneous rock of ultramafic composition, composed almost entirely of the mineral olivine, with minor pyroxene, chromite, and pyrope

dwarf planet a celestial body that is in orbit around the Sun, has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, has not cleared the neighborhood around its orbit, and is not a satellite

dwarfs (stars) stars that have a size that is normal for their mass, that lie on the main sequence curve, and that are in the process of converting hydrogen to helium by nuclear fusion in their cores. Dwarfs are also classified as any star with a radius comparable to or smaller than the Earth's Sun, which is classified as a yellow dwarf.

Earth the third planet from the center of our solar system, located between Venus and Mars at a distance of 93 million miles (150 × 10^6 km) from the Sun

earthflow a generally slow-moving downslope flow that forms on moderate slopes with adequate moisture and develops preferentially in fine-grained deformable soils such as clays, as well as rocky soils that have a silt or clay matrix. Earthflows can contribute large amounts of sediment to streams and rivers and typically move in short periods of episodic movement or relatively steady movement in response to heavy rainfall events, earthquakes, irrigations, or other disturbances. Most earthflows move along a basal shear surface, are characterized by internal deformation of the sliding material, and do not fail catastrophically but do cause significant damage to infrastructure.

earthquake a sudden release of energy from slip on a fault, an explosion, or other event that causes the ground to shake and vibrate, associated with the passage of waves of energy released at its source. An earthquake originates in one place and then spreads out in all directions along the fault plane.

ebb tide outgoing tide

ecliptic plane the relatively flat plane that contains most of the planetary orbits around the Sun

eclogite a coarse grained mafic (basaltic in composition) metamorphic rock, containing red garnet and a green sodium-rich amphibole called omphacite. Eclogite is a high-pressure metamorphic rock, formed at cool temperatures and high pressures, so it is typically taken as an indicator of subduction zone metamorphism of a basaltic precursor.

economic geology the science of the study of earth materials that can be used for economic or industrial purposes

ecosystem a collection of the organisms and surrounding physical elements that together function as an ecological unit

edge wave a secondary wave, associated with tsunamis and other waves, that forms as the water from one wave crest retreats, moves back to sea, and interacts with the next incoming wave. Some of this water moves quickly sideways along the coast, setting up a new independent set of waves that oscillates up and down in amplitude along the coast, typically with a wavelength that is double that of the original tsunami.

ejecta material thrown out of an impact crater during an impact event

elastic rebound theory this theory states that recoverable (also known as elastic) stresses build up in a material until a specific level or breaking point is reached. When the breaking point or level is attained, the material suddenly breaks, releasing energy and stresses, causing an earthquake.

electromagnetic radiation self-propagating waves that move through matter or a vacuum, consisting of both electric and magnetic field components that vibrate perpendicular to each other and perpendicular to the direction of energy propagation. Electromagnetic radiation is classified into types according to frequency of the wave, in order of increasing frequency from radio waves, to microwaves, terahertz radiation, infrared, visible, and ultraviolet radiation, X-rays, and gamma rays.

electron-degenerate matter a form of degenerate matter in collapsed stars created where the pressure of overlying matter forces all of the electrons surrounding the nucleus into lowest energy quantum states

El Niño one of the better-known variations in global atmospheric circulation patterns that causes a warm current to move from the western Pacific to the eastern Pacific and that has global consequences in terms of changes in weather patterns. Full name is El Niño–Southern Oscillation (ENSO)

emission nebulae hot glowing clouds of ionized interstellar gas

enderbite granulite-facies metamorphic rock containing orthopyroxene, quartz, and plagioclase

entrainment the picking up of particles from the bed load of a stream and the erosion of material from the banks

environmental geology an applied interdisciplinary science focused on describing and understanding human interactions with natural geologic systems, where different systems of the lithosphere, biosphere, hydrosphere, and atmosphere interact, and changes in one system are seen to influence the other systems

Eocene the middle epoch of the Paleogene (Lower Tertiary) period, ranging from 57.8 million years ago to 36.6 million years ago, and divided from base to top into the Ypresian, Lutetian, Bartonian, and Priabonian ages

eolian sediments deposited by wind

epeirogenic a term referring to the vertical movements of continents

ephemerides predictions of when certain stars and planets would be found in specific locations

epicenter the point on the Earth's surface that lies vertically above the focus of an earthquake

equations of state thermodynamic equations that describe the state of matter under a given set of physical conditions such as temperature, pressure, volume, or internal energy

equinox the time, twice a year, that the tilt of the Earth places the Sun directly over the equator, and when the length of the day and night at the equator are equally long

erosion a group of processes that cause Earth material to be loosened, dissolved, abraded, or worn away and moved from one place to another

erosional coast a coastline that is actively eroding, typically with erosional cliffs or headlands

escape tectonic escape is process where a large block of rock slides sideways and moves out of a tectonic collision zone, generally moving toward an open ocean basin

estuary embayment along the coast that is open to the sea and influenced by tides and waves. Estuaries also have significant freshwater influence derived from river systems that drain into the head of the bay. The fresh and salt water mix within the estuary.

eukaryote an organism consisting of one or more cells possessing nuclei and membrane-bound organelles

eustatic sea-level change a sea-level change shown to be global in scale. Sea levels may also rise or fall for local (noneustatic) reasons, such as tectonic subsidence, or global reasons, such as melting of glaciers.

evaporation the conversion of a liquid to a vapor, such as water to vapor

evaporites sedimentary rocks made of water-soluble minerals that formed during the evaporation of a body of surface water, such as a lake or small ocean basin

evolution the cumulative and irreversible change of organisms through time. Results of this process explain the distribution and diversity of life throughout Earth history.

exfoliation a weathering process where rocks spall off in successive shells, like the skin of an onion. Exfoliation is caused by differential stresses within a rock formed during chemical weathering processes.

expansive clay and soils soils that add layers of water molecules between the plates of clay minerals (made of silica, aluminum, and oxygen), loosely bonding the water in the mineral, and that are capable of expanding by up to 50 percent more than their dry volume

extensional collapse a late-stage of orogenic evolution in which the crust is extended along numerous normal faults, initiated by the crust becoming too thick to be supported by weak rock layers at depth

extensional plate boundaries *See* divergent boundaries.

fabric a general term referring to the orientation of minerals in a rock, forming cleavage, foliation, lineation, gneissosity, or other structural elements

facies a distinctive set of igneous, metamorphic, or sedimentary characteristics of a group of rocks that separate and differentiate them from surrounding groups of rocks

falls in mass wasting, when regolith moves freely through the air and lands at the base of the slope or escarpment

fanglomerate a type of sedimentary deposit in which conglomerates are deposited as an alluvial fan derived from nearby uplifted mountains

fetch the distance over which the wind blows over water, forming waves of a particular wave set

fireball streak of light that moves across sky, produced by a meteorite or comet burning up in the atmosphere

firn frozen water that is transitional in density between snow and ice

fjords glacially carved, steep-sided valleys that are open to the sea

flash floods floods that rise suddenly, typically as a wall of water in a narrow canyon

flood abnormally high water, typically occurs when a river flows over its banks

flood basalt thick sequences of basaltic lava that cover very large areas of the continents or oceans, also known as traps or large igneous provinces

floodplain flat areas adjacent to rivers that naturally flood and are generally composed of unconsolidated sediments deposited by the river

flood tide incoming tide

flower structure a distinctive geometry of faults where a major nearly vertical strike-slip fault in the center of a mountain range is succeeded outward on both sides by more shallow dipping faults with strike-slip and thrust components of motion. A cross section drawn through these types of structures resembles a flower or a palm tree

flows in mass wasting, movements of regolith, rock, water, and air in which the moving mass breaks into many pieces that flow in a chaotic mass movement

fluvial deposits and landforms created by the action of flowing rivers and streams, and also the processes that occur in these rivers and streams

flysch a thick group of turbidites and shale deposited at the same time as mountain building, typically in a deep sea–basin environment or a forearc basin on a continent

focus the point in the Earth where the earthquake energy is first released, representing the area on one side of a fault that actually moves relative to the rocks on the other side of the fault plane. After the first slip event, the area surrounding the focus experiences many smaller earthquakes as the surrounding rocks also slip past each other to even out the deformation caused by the initial earthquake shock.

fold a geological structure in which deformation of the rock unit bends strata into inward or outward dipping layers. Inward dipping layers form synclines, and outward dipping layers form anticlines.

fold interference pattern a complexly shaped structure produced when a layer is affected by more than one generation of fold, typically producing strange three-dimensional warps and bends of the rock layers

forearc the part of a magmatic arc on the oceanward side of the arc, including the forearc basin, accretionary wedge, and trench. Many tsunamis are generated by thrust type earthquakes that uplift large sections of the forearc, displacing huge masses of water.

foredune ridge a linear ridge of sand that marks the boundary between the beachface and backbeach area

foreland basin a tectonic depression that forms adjacent to a mountain belt. Foreland basins form because the weight of the adjacent mountain belt causes the crust and entire lithosphere to bend in a process called flexure to accommodate the weight of the mountain belt.

foreshore a flat, seaward-sloping surface that grades seaward into the ridge and runnel. The foreshore is also known as the beachface.

fossil any remains, traces, or imprints of any plants or animals that lived on the Earth

fractionation in geochemistry, a separation process in which one phase (melt, solid, or fluid) of a mixture is removed in small quantities, changing the bulk composition of the remaining mixture. An example is when a crystal phase separates out of a magma by sinking to the bottom of the magma chamber, removing the chemical elements in those crystals from the overall melt composition, which then attains a different composition than before the crystals settled.

fracture any break in a rock or other body that may or may not have any observable displacement. Fractures include joints, faults, and cracks formed under brittle deformation conditions and are a form of permanent (nonelastic) strain.

fracture zone in oceanic crust, the zone that appears to be an extension of the transform fault but is not a plate boundary. Fracture zones represent the places where two parts of the same plate with different ages are juxtaposed by seafloor spreading.

fracture zone aquifer water that is stored in fractures in crystalline bedrock systems and is extractable for use by humans. Many buried granite and other bedrock bodies are cut by many fractures, faults, and other cracks, some of which may have open spaces along them. Fractures at various scales represent zones of increased porosity and permeability. They may form interconnected networks, and therefore, are able to store and carry vast amounts of water, forming fracture zone aquifers.

fusilinids fossils of a group of single-celled animals belonging to the phylum Protozoa. They grew in coral-like colonies, forming columnar, snail-like, or cigar-like shapes

gabbro a coarse-grained, dark, igneous intrusive rock consisting of the minerals pyroxene, plagioclase, amphibole, and olivine. Gabbro is the plutonic equivalent of basalt and is common in oceanic crust.

Gaia hypothesis a hypothesis suggesting that Earth's atmosphere, hydrosphere, geosphere, and biosphere interact as a self-regulating system that maintains conditions necessary for life to survive

galaxies gravitationally bound assemblages of stars, dust, gas, radiation, black holes, and dark matter. Most contain vast numbers of star systems and are located at enormous distances from the Milky Way Galaxy, such that the light reaching Earth from these galaxies was generated billions of years ago.

galaxy cluster a group of 50 or more galaxies held together by mutual gravitational attraction

gas hydrates solid, ice-like, water-gas mixtures that form at temperatures between 40° and 43°F (4–6°C) and pressures above 50 atmospheres. As a type of clathrate, gas hydrates consist of lattices that enclose or trap other molecules—typically methane gas, but also ethane, butane, propane, carbon dioxide, and hydrogen sulfides.

geochemical cycles the transportation, cycling, and transformation of the different chemical elements through various reservoirs or spheres in the Earth system, including the atmosphere, lithosphere, hydrosphere, and biosphere

geochemistry the study of the distribution and amounts of elements in minerals, rocks, ore bodies, rock units, soils, the Earth, atmosphere, and by some accounts, other celestial bodies, and the principles that govern the distribution and migration of these elements

geochronology the study of time with respect to Earth history including both absolute and relative dating systems as well as correlation methods

geodesy the study of the size and shape of the Earth and its gravitational field, and the determination of the precise locations of points on the surface

geodynamics the branch of geophysical science that deals with forces and physical processes in the interior of the Earth

geographic information systems (GIS) computer application programs that organize and link geographic-related information in a way that enables the user to manipulate that information in a constructive way. They typically integrate a database management system with a graphics display that shows links between different types of data.

geoid an imaginary surface near the surface of the Earth, along which the force of gravity is the same and equivalent to that at sea level

geological hazards natural geologic processes ranging from earthquakes and volcanic eruptions to the slow downhill creep of material on a hillside and the expansion of clay minerals in wet seasons. These processes are considered hazardous when they go to extremes and interfere with the normal activities of society.

geomagnetism the study of the Earth's magnetic field, including its generation, strength, and changes over time

geomorphology the study of the surface features and landforms on Earth

geophysics the study of the Earth by quantitative physical methods, with different divisions including solid-Earth geophysics, atmospheric and hydrospheric geophysics, and solar-terrestrial physics

geosyncline an obsolete term for a subsiding linear trough or basin formed by the accumulation of sedimentary rocks deposited in a basin and subsequently compressed, deformed, and uplifted into a mountain range, with attendant volcanism and plutonism caused by the melting of the deep sediments. Geosyncline theory was replaced by the theory of plate tectonics to explain features of basins and mountain ranges.

geothermal gradient a measure of how the temperature changes with increasing depth in the Earth

geyser springs in which hot water or steam sporadically or episodically erupts as jets from an opening in the surface, in some cases creating a tower of water hundreds of feet (tens of meters) high

glacial drift a general term for all sediment deposited directly by glaciers or by glacial meltwater in streams, lakes, and the sea

glacial erratic glacially deposited rock fragments with compositions different from underlying rocks

glacial marine drift sediment deposited on the seafloor from floating ice shelves or bergs, including any isolated pebbles or boulders that were initially trapped in glaciers on land, then floated in icebergs that calved off from tidewater glaciers

glacial moraine piles of sand, gravel, and boulders deposited by a glacier

glacial outwash plain a generally flat plain of gravel, sand, and other sediments deposited by meltwater in front of the terminus of a glacier

glacial rebound a process during which an ice sheet melts, leading to the upward rise (rebound) of a continent in response to the reduced weight load upon it

glacial striations scratches on the surface of bedrock, formed from a glacier dragging boulders across the bedrock surface

glacier any permanent body of ice (recrystallized snow) that shows evidence of gravitational movement

global warming a trend in climate characterized by progressive increases in the global average yearly temperature over many years

gneiss high-grade, regional metamorphic rock, with a medium to coarse grain size, showing a pronounced layering called gneissic foliation

Gondwana a late Proterozoic to Paleozoic supercontinent of the southern hemisphere, that included present day Africa, South America, Australia, India, Arabia, Antarctica, and many small fragments

graded stream a stream that has gradually adjusted its gradient to reach an equilibrium between sedimentary load, slope, and discharge

gradient in geology, a measure of the vertical drop in elevation over a given horizontal distance

granite, granodiorite a common igneous rock type found in the continental crust. The density of granodiorite is 2.6 g/cm^3; its mineralogy includes quartz, plagioclase, biotite, and some potassium feldspar. Granite has more quartz than granodiorite. The volcanic or extrusive equivalent of granite is rhyolite, and of granodiorite, andesite.

granular flow a downslope flow in which the full weight of the flowing sediment is supported by grain-to-grain contact between individual grains

granulite a high-grade metamorphic rock formed at high pressures and temperatures, and characteristic of the middle to deep crust

gravity the attraction between any body in the universe and all other bodies

gravity anomaly geologically significant variations in gravity

gravity wave in fluid dynamics, waves generated in a fluid medium or at the interface between two fluids, such as air and water. In astrophysics and in general relativity theory, gravity waves can be thought of as gravitational radiation that results from a change in the strength of a gravitational field. Any mass that accelerates through space will produce a small distortion in the space through which it is traveling, producing a change in the gravitational field, or a gravity wave, that should be emitted at the speed of light.

great earthquakes earthquakes with magnitude greater than 8.0 on the Richter scale that often cause a vast amount of destruction and release a huge amount of energy. Most great earthquakes occur at convergent plate margins.

Great Ice Ages a term referring to the late Pleistocene glaciation

greenhouse effect a phenomenon characterized by abnormal warmth on Earth in response to the atmosphere's trapping incoming solar radiation by greenhouse gases

greenhouse gases gases, such as carbon dioxide (CO_2), that when built up in the atmosphere tend to keep solar heat in the atmosphere, resulting in global warming

greenschist a metamorphic rock that is generally derived from mafic rocks, altered to mineral assemblages of low regional metamorphic grade, called greenschist facies

greenschist facies a low to medium grade metamorphic zone

greenstone belts elongate accumulations of generally mafic volcanic and plutonic rocks, typically associated with immature graywacke types of sedimentary rocks, banded-iron formations, and less commonly carbonates and mature sedimentary rocks. Most greenstone belts are Archean or at least Precambrian in age, although similar sequences are known from orogenic belts of all ages. Most greenstone belts are metamorphosed to greenschist through amphibolite facies and are intruded by a variety of granitoid rocks.

Grenville province and Rodinia the youngest region of the Canadian shield, located outboard of the Labrador, New Quebec, Superior, Penokean, and Yavapai-Mazatzal provinces. It is the last part of the Canadian shield to experience a major deformational event, this being the Grenville orogeny at about 1.0 billion years ago, which was responsible for forming many folds and faults throughout the entire region during the amalgamation of numerous continents to form the supercontinent of Rodinia.

greywacke a sandy sedimentary rock with mud particles between the sand grains

groin walls of rock, concrete, or wood built at right angles to the shoreline that are designed to trap sand from longshore drift and replenish a beach

ground breaks fissures or ruptures that form where a fault cuts the surface and may be associated with mass wasting, or the movements of large blocks of land downhill. These ground breaks may have horizontal, vertical, or combined displacements across them and may cause considerable damage.

ground level the elevation of the land surface above sea level

ground motion shaking and other motion of the ground associated with the passage of seismic waves. The amount of ground motion associated with an earthquake generally increases with the magnitude of the earthquake, but depends also on the nature of the substratum. Ground motions are measured as accelerations, which indicate the rate of change of motion.

groundwater all the water contained within spaces in bedrock, soil, and regolith

Hadean Era the earliest time in Earth history, ranging from accretion at 4.56 billion years ago, until the time of the oldest rocks preserved at 3.96 billion years ago

Hadley cell belt of air that encircles the Earth, rising along the equator, dropping moisture as it rises in the tropics. As the air moves away from the equator at high elevations, it cools, becomes drier, and then descends at 15°–30°N and S latitude where it either returns to the equator or moves toward the poles. Similar circulation cells called mid-latitude cells dominate the air circulation between 30° and 60°N and S latitude, and polar cells occupy latitudes above 60°.

harzburgite an ultramafic igneous rock of the peridotite family, consisting of olivine and pyroxene. Harzburgite is a common rock in the mantle section of ophiolitic rock sequences.

heat capacity a measure of how much energy can be absorbed by a body without its changing temperature

heat of vaporization amount of energy to change water from a liquid state to a vapor

Heinrich Events specific intervals in the sedimentary record showing ice-rafted debris in the North Atlantic

helioseismology the science of studying the oscillations of the Sun

helium flash an uncontrolled explosive burning of helium that lasts for a few hours in the core of a red giant star as its core undergoes the conversion to helium fusion

heterotrophs organisms that cannot manufacture their own food but must intake carbon and nitrogen from their environment in the form of complex organic molecules

high-constructive deltas deltas that form where the fluvial transport dominates the energy balance on the delta. These deltas dominated by riverine processes are typically elongate, such as the modern delta at the mouth of the Mississippi.

high-destructive deltas deltas that form where the tidal and wave energy is high and much of the fluvial sediment gets reworked before it is finally deposited. In wave-dominated high-destructive deltas, sediment typically accumulates as curved barriers near the mouth of the river. Examples of wave-dominated deltas include the Nile and the Rhone deltas.

historical geology the science that uses the principles of geology to reconstruct and interpret the history of the Earth

horn peak in mountains that forms where three cirques meet

hothouse a time when the global climate was characterized by very hot conditions for an extended period

hot spot an area of unusually active magmatic activity that is not associated with a plate boundary. Hot spots are thought to form above a plume of magma rising from deep in the mantle.

Hubble's constant a constant of proportionality that gives the relationship between recessional velocity and distance in Hubble's Law

Hubble's law the law that states that the recessional velocity of a galaxy is proportional to its distance from the observer

hurricanes intense tropical storms with sustained winds of more than 74 miles per hour (119 km/hr) characterized by a central eye with calm or light winds and clear skies, surrounded by an eye wall, which is a ring of very tall and intense thunderstorms that spin around the eye, with some of the most intense winds and rain of the entire storm system. The eye is surrounded by spiral rain bands that spin counterclockwise in the Northern Hemisphere (clockwise in the Southern Hemisphere) in toward the eye wall, moving faster and generating huge waves as they approach the center. These storms are known as hurricanes if they form in the northern Atlantic or eastern Pacific Oceans, cyclones if they form in the Indian Ocean or near Australia, or typhoons if they form in the western Pacific Ocean.

hydraulic gradient the pressure difference between the elevation of the source area and the discharge area of an aquifer

hydraulic piping where water finds a weak passage through a levee

hydrocarbons and fossil fuels gaseous, liquid, or solid organic compounds consisting of hydrogen and carbon. Petroleum is a mixture of different types of hydrocarbons derived from the decomposed remains of plants and animals.

hydrologic (water) cycle sequential changes, both long- and short-term, in the Earth's hydrosphere, involving the movement and physical changes of water in the atmosphere and on the Earth's surface, involving processes such as precipitation, evaporation, transpiration, freezing, and melting

hydrosphere a dynamic mass of liquid, continuously on the move between the different reservoirs on land and in the oceans and atmosphere. The hydrosphere includes all the water in oceans, lakes, streams, glaciers, atmosphere, and groundwater, although most water is in the oceans.

hydrothermal a term used to describe any process that involves high temperature fluids, often in reference to hot springs, geysers, and related activities

ice ages times when the global climate was cold and large masses of ice covered many continents

igneous rocks rocks that have crystallized from a molten state known as magma. These include plutonic rocks, crystallized below the surface, and volcanic rocks, that have crystallized at the surface.

imbrication an arrangement of planar bodies in a regular stacked way that resembles a tipped over line of dominoes

impact crater a generally bowl-shaped depression excavated by the impact of a meteorite or comet with the Earth

impact glass glass produced by the sudden melting and homogenization and sudden cooling of rock during a meteorite impact event

impactor a general name for an object that strikes and creates a crater in another object

index fossil a fossil that is used to identify and define geological periods, or faunal stages. Ideal index fossils are short-lived, have a broad distribution, and are easy to identify.

inflationary theory a modification of the big bang theory, suggesting that the universe underwent a period of rapid expansion immediately after the big bang

infrared a type of electromagnetic radiation with a wavelength between 750 nanometers and 1 mm, longer than visible light but shorter than terahertz and microwave radiation

inselbergs steep-sided mountains or ridges that rise abruptly out of adjacent monotonously flat plains in deserts

interglacial period a period such as the present climate epoch, characterized as being between advances and retreats of major continental ice sheets. The glaciers could return, or global warming could melt the remaining polar ice, taking the planet out of the glacial epoch.

Intergovernmental Panel on Climate Change (IPCC) a scientific intergovernmental body set up by the World Meteorological Organization (WMO) and by the United Nations Environment Program (UNEP). The IPCC is open to all member countries of WMO and UNEP. Governments participate in plenary sessions of the IPCC where main decisions about the IPCC work program are taken and reports are accepted, adopted, and approved. They also participate in the review of IPCC reports. The IPCC includes hundreds of scientists from all over the world who contribute to the work of the IPCC as authors, contributors, and reviewers. As a United Nations body, the IPCC work aims at the promotion of the United Nations human development goals.

interstellar medium the areas or voids between the stars and galaxies, representing a nearly perfect vacuum, with a density a trillion trillion times less than that of typical stars

intertidal flat a flat area within the tidal range that sheltered from waves, dominated by mud, devoid of vegetation, and accumulating sediment; also called tidal flat

intertidal zone the area between the high-tide line and the low-tide line

intraplate earthquake a rare, occasionally strong type of earthquake that occurs in the interior of plates far from plate boundaries. The origins of these earthquakes are not well understood.

ionization the process of converting an atom or molecule into a charged ion by adding or removing charged particles such as electrons

iron meteorites meteorites that are composed mostly of metallic material

island arc *See* magmatic arc.

isoclinal folds folds in which relatively flat limbs on either side of the curved hinge are parallel to each other

isostasy a principle that states that the elevation of any large segment of crust is directly proportional to the thickness of the crust

isotopes forms of an element that have different atomic masses; all isotopes of an element have the same number of protons in the nucleus but differ in the number of neutrons

jet stream high-level, narrow, fast-moving currents of air that are typically thousands of miles (km) long, hundreds of miles (km) wide, and several miles (km) deep

Jupiter The fifth planet from the Sun, Jupiter is a gaseous giant of the solar system, with more than twice the mass of all the other planets combined, estimated at 1.9×10^{27} kilograms, or 318 Earth masses, and a radius of 44,268 miles (71,400 km), or 11.2 Earth radii

karst a type of landscape formed by the dissolution of underlying bedrock, typically limestone, characterized by caves, sinkholes, collapsed caves, and isolated towers

karst terrains areas that are affected by groundwater dissolution, cave complexes, and sinkhole development

katabatic wind a strong downhill wind of high-density air that moves downhill from a mountain, typically in a valley, and often at high velocity

Kepler's third law a law of planetary motion that states that the squares of the orbital periods of planets are directly proportional to the cubes of the axes, so that as the length of the orbit increases with distance, the orbital speed decreases

kerogen organic chemical compounds found in sedimentary rocks

khondalite granulite facies metamorphic rock containing quartz, sillimanite, garnet, K-feldspar, plagioclase, and graphite

kimberlite an unusual volcanic rock containing mixtures of material derived from the upper mantle and complex water-rich magmas. Many kimberlites intrude explosively, forming large pipes that fill with the magma, and many contain diamonds.

kinematic indicators features in deformed rocks that give clues about the sense of shearing in the deformational history of the rock. Typical kinematic indicators include deformed mineral grains, asymmetric foliations, and rotated grains.

kinematics the scientific study of motions without consideration of forces or stresses involved. Most of plate tectonics and structural geology are kinematic models.

Kuiper belt a distant part of the solar system, extending from 30–49 astronomical units, and containing many comets and asteroids

lagoon a rare class of restricted coastal bay that is separated from the ocean by an efficient barrier that blocks any tidal influx and that does not have significant freshwater influx from the mainland

lahar a mudflow formed by the mixture of volcanic ash and water. Lahars are common on volcanoes, both during and for years after major eruptions.

laminar flow in a stream, where paths of water particles are parallel and smooth and the flow is not very erosive. Resistance to flow in laminar systems is provided by internal friction between individual water molecules, and the resistance is proportional to flow velocity.

landslide a general name for any downslope movement of a mass of bedrock, regolith, or a mixture of rock and soil, commonly used to indicate any mass-wasting process

large igneous provinces, flood basalt deposits that include vast plateaus of basalts, covering large areas of some continents, exhibiting a tholeiitic basalt composition, but some show chemical evidence of minor contamination by continental crust. They are similar to anomalously thick and topographically high seafloor known as oceanic plateaus and to some volcanic rifted passive margins. Also known as continental flood basalts, plateau basalts, and traps

latent heat the amount of energy, in the form of heat, that is absorbed or released by a substance during a change in state such as from a liquid to a solid

laterite a red-colored soil rich in iron and aluminum that forms by intense weathering of underlying bedrock in tropical regions. The most common minerals in laterite are kaolinite, goethite, hematite, and gibbsite.

lava magma, or molten rock, that flows at the surface of the Earth

leeward the side of a mountain facing away from oncoming winds

leptynite granulite facies metamorphic rock containing quartz, garnet, K-feldspar, plagioclase, amphibole, sillimanite, and biotite

lherzolite an ultramafic igneous rock of the peridotite family consisting of olivine, orthopyroxene, and clinopyroxene, thought to be a major component of the mantle. Partial melt of lherzolite mantle in mid-ocean ridges forms a residual peridotite known as harzburgite, plus oceanic crust.

limestone a sedimentary carbonate rock made predominantly of the mineral calcite ($CaCO_3$)

lineation a penetrative linear element in a rock, typically formed by the alignment of minerals or deformed grains, pebbles, fossils, or other structural elements

liquefaction a process in which sudden shaking of certain types of water-saturated sands and muds turn these once-solid sediments into a slurry, a substance with a liquid-like consistency. Liquefaction occurs when individual grains move apart, and then water moves up in between the individual grains making the whole water/sediment mixture behave like a fluid.

lithosphere the rigid outer shell of the Earth that is about 75 miles (125 km) thick under continents and about 45 miles (75 km) thick under oceans. The basic theorem of plate tectonics is that the lithosphere of the Earth is broken into about 12 large rigid blocks or plates that are all moving relative to one another.

loess a deposit of fine-grained, wind-blown dust

longshore current the movement of water parallel to the coast along the beachface, caused by the oblique approach of waves

longshore drift the gradual transport of sand along a beach, caused by waves washing sand diagonally up the beachface, and gravity pulling the sand back down the beachface perpendicular to the shoreline

mafic an adjective describing generally dark-colored igneous rocks that are composed chiefly of iron-magnesium rich minerals and typically have silica contents from 45–52 percent, as determined by chemical analysis. Common mafic igneous rocks include basalt and gabbro.

magma molten rock, at high temperature. When magma flows on a surface, it is known as lava.

magmatic arc a line of volcanoes and igneous intrusions that forms above a subducting oceanic plate along a convergent margin. Island arcs are built on oceanic crust, and continental margin magmatic arcs are built on continental crust.

magnetic field, magnetosphere Earth's magnetic field is generated within the core of the planet. The field is generally approximated as a dipole, with north and south poles, and magnetic field lines that emerge at the magnetic south pole and reenter at the magnetic north pole. The field is characterized at each place on the planet by an inclination and a declination of the magnetic flux lines.

magnetic isogonic lines lines of constant magnetic declination

main sequence a continuous band of stars that appears on a plot of luminosity versus temperature for stars, indicating a stable relationship between luminosity, temperature, and star mass

mangal a dense, coastal, mangrove-dominated ecosystem

mantle the layer of the Earth between the crust and the core, containing dense, highly viscous mafic rocks that flow in convection cells

mantle plumes linear plumes of hot material that upwell from deep within the mantle, perhaps even from the core-mantle boundary

mantle root a very thick (up to 200 miles, or > 300 km) section of lithospheric mantle beneath many Archean cratons, containing cold material from which a melt has been removed, adding stability to the craton

marine terraces wave-cut benches or platforms that are uplifted above sea level, typically occurring in groups at different levels reflecting different stages of uplift

Mars the fourth planet from the Sun. Mars is only 11 percent of the mass of Earth and has an average density of 3.9 grams per cubic centimeter and a diameter of 4,222 miles (6,794 km).

mass extinction a time when large numbers of species and individuals within a species die off. Mass extinction events are thought to represent major environmental catastrophes on a global scale. In some cases these mass extinction events can be tied to specific likely causes, such as meteorite impact or massive volcanism, but in others their cause is unknown. The Earth's biosphere has experienced five major and numerous less-significant mass extinctions in the past 500 million years (in the Phanerozoic era). These events occurred at the end of the Ordovician, in the late Devonian, at the Permian/Triassic boundary, at the Triassic/Jurassic boundary, and at the Cretaceous/Tertiary (K/T) boundary. Many mass extinctions can be shown to have occurred in less than a million or two years.

mass wasting the movement of material downhill without the direct involvement of water

meander a gentle bend in the trace of a river

mechanical weathering the disintegration of rocks, generally by abrasion

medical geology an emerging science that studies the effects of geological materials, processes, and trace elements in the environment on human and animal health

megaton a mass equal to 1,000,000 tons, at 2,000 pounds per ton in the United States. One ton is equal to 0.907 metric tonnes.

mélange a complexly mixed assemblage of rocks, characteristically formed at subduction zones

Mercalli intensity scale a scale that measures the amount of vibration people remember feeling for low-magnitude earthquakes and measures the amount of damage to buildings in high-magnitude events

Mercury the closest planet to the Sun, with a mass of only 5.5 percent of the Earth's, a diameter of 3,031 miles (4,878 km), and an average density of 5.4 grams per cubic centimeter

mesosphere region of the atmosphere that lies above the stratosphere, extending between 31 and 53 miles (85 km)

Mesozoic the fourth of five main geologic eras. The Mesozoic falls between the Paleozoic and Cenozoic, and includes the Triassic, Jurassic, and Cretaceous Periods. The era begins at 248 million years ago at the end of the Permian-Triassic extinction event and continues to 66.4 million years ago at the Cretaceous-Tertiary (K-T) extinction event.

metamorphic aureole a thin band of metamorphic rocks that are transposed from their initial state into their metamorphic equivalents in response to heating by an adjacent geologic body. Contact aureoles form next to igneous intrusions, and dynamothermal aureoles form beneath hot thrust sheets such as ophiolitic complexes.

metamorphism changes in the texture and mineralogy of a rock due to changes in the pressure, temperature, and composition of fluids, typically from plate margin processes

metasomatic the group of metamorphic processes responsible for changing a rock's composition or mineralogy by the gradual replacement of one component by another through the movement and reaction of fluids and gases in the pore spaces of a rock

meteor a streak of light in the sky formed by the burning of a meteorite or comet as it moves through the Earth's atmosphere

meteoric Water that has recently come from the Earth's atmosphere is called meteoric water. The term is usually used in studies of groundwater, to distinguish water that has resided in ground for extended periods of time versus water that has recently infiltrated the system from rain, snow melt, or stream infiltration.

meteorite rocky or metallic body that has fallen to Earth from space

meteorology the study of the Earth's atmosphere, along with its movements, energy, and interactions with other systems, and weather forecasting

microplate Most tectonic plates are large, typically thousands of miles (km) across. In some situations, such as during rifting and continental collision, relatively small areas of the continental lithosphere break up into many much smaller plates, typically tens to hundreds of miles across, known as microplates.

mid-ocean ridge system a 40,000-mile- (65,000-km-) long mountain ridge that runs through all the major oceans on the planet. The mid-ocean ridge system includes vast outpourings of young lava on the ocean floor and represents places where new oceanic crust is being generated by plate tectonics.

migmatite a metamorphic rock that contains layers or lenses of partially melted country rock interlayered or mixed with the original rock, which is typically strongly deformed

Milankovitch cycles variations in the Earth's climate that are caused by variations in the amount of incoming solar energy, induced by changes in the Earth's orbital parameters including tilt, eccentricity, and wobble

mineral any naturally occurring inorganic solid that has a characteristic chemical composition, a highly ordered atomic structure, and specific physical properties

mineralogy the branch of geology that deals with the classification and properties of minerals

Mohorovicic discontinuity the transition from crust to mantle, generally marked by a dramatic increase in the velocity of compressional seismic waves, from typical values of less than 4.7 miles per second to values greater than 4.85 miles per second (7.6–7.8 km/s)

molasse nonmarine, irregularly stratified conglomerate, sandstone, shale, and coal deposited during the late stages of mountain building

molecular attraction the force that makes thin films of water stick to things, instead of being forced to the ground by gravity

monsoon a wind system that influences large regions and has seasonally persistent patterns with pronounced changes from wet to dry seasons

monzonite intrusive igneous rock of intermediate composition, including roughly equal amounts of plagioclase and orthoclase feldspars, with minor hornblende, biotite, and other minerals. A rock with more than 10 percent quartz is classified as a quartz monzonite.

moraine ridgelike accumulations of glacial drift deposited at the edges of a glacier. Terminal moraines mark the farthest point of travel of a glacier, whereas lateral moraines form along the edges of a glacier.

morphodynamics the study of the effects of local coastal features on tsunami characteristics

mudflow a downslope flow that resembles a debris flow, except it has a higher concentration of water (up to 30 percent), which makes it more fluid, with a consistency ranging from soup to wet concrete. A mudflow often starts as a muddy stream in a dry mountain canyon, and as it moves it picks up more and more mud and sand, until eventually the front of the stream is a wall of moving mud and rock.

mylonite a strongly deformed rock that forms in ductile shear zones under dynamic recrystallization, forming a strongly foliated and lineated rock that is finer in grain size than the original rock

nappe a large sheetlike body of rock that has been moved by tectonic transport, such as thrusting, significantly far from its place of origin

neap tides tides that occur during the first and third quarters of the Moon and are characterized by lower than average tidal ranges

nebula an interstellar cloud of dust, gas, and plasma

Neogene the second of three periods of the Cenozoic, including the Paleogene, Neogene, and Quaternary, and the second of two subperiods of the Tertiary, younger than Paleogene. Its base is at 23.8 million years ago, and its top is at 1.8 million years ago, followed by the Quaternary period.

Neolithic in archeology, a term for the last division of the Stone Age, during which time humans developed agriculture and domesticated animals.

The transition from hunter-gatherer and nomadic types of existence to the development of farming took place about 10,000–8,000 years ago in the Middle East.

Neptune the eighth and farthest planet from the center of the solar system. Neptune orbits the Sun at a distance of 2.5 billion miles (4.1 billion km, or 30.1 astronomical units), completing each circuit every 165 years, and rotating about its axis every 18 hours. Neptune has a diameter of 31,400 miles (50,530 km) and a mass of more than 17.21 times that of Earth. Its density of 1.7 grams per cubic centimeter shows that the planet has a dense rocky core surrounded by metallic, molecular, and gaseous hydrogen, helium, and methane, giving the planet its blue color.

neutrino elementary particle that moves at nearly the speed of light, has no electrical charge, and passes through matter nearly undisturbed

neutron degeneracy pressure a strong force generated in collapsing giant stars by the repulsive forces between neutrons when they are forced closely together

nova a general name for a type of star that vastly increases in brightness (by up to 10,000 times) over very short periods of time, typically days or weeks

nucleosynthesis the production of heavier elements by the nuclear fusion of lighter elements in stars, novas, and supernovas

nucleus in the astronomical sense, the inner part of a comet, consisting of rock and ice. Also, the inner part of an atom consisting of protons and neutrons

nuée ardente a fast-moving glowing hot cloud of ash that can move down the flanks of volcanoes at hundreds of miles (km) per hour during eruptions. Nuée ardentes have been responsible for tens of thousands of deaths during eruptions.

nunatak an isolated mountain peak protruding from the top of a continental ice sheet or large mountain glacier

ocean basin submarine topographic depressions underlain by oceanic (simatic) crust

ocean currents the movement paths of water in regular courses, driven by the wind and thermohaline forces across the ocean basins

oceanic plateau regions of anomalously thick oceanic crust and topographically high seafloor. Many have oceanic crust that is 12.5–25 miles (20–40 km) thick and rise thousands of meters above surrounding oceanic crust of normal thickness.

oceanography the study of the physical, chemical, biological, and geological aspects of the ocean basins

olistostromes chaotic sedimentary deposits consisting of blocks of one rock type mixed with another. Most olistostromes are thought to be formed by the downslope movement of sedimentary packages.

ontogeny the development of an individual organism from young to old age, as from a tadpole to a frog

oolite a sedimentary deposit consisting of many sand-sized carbonate grains with an onion skin–like texture that form by rolling on the seafloor in shallow agitated waters, continuously being precipitated around a hard nucleus. Oolites form in waters that are saturated with calcium carbonate, typically in areas of high evaporation and agitation, which releases carbon dioxide.

Oort cloud a roughly spherical region containing many comets and other objects, extending from about 60 astronomical units beyond 50,000 AU, or about 1,000 times the distance from the Sun to Pluto, or about a light-year

ophiolite a group of mafic and ultramafic rocks including pillow lavas and plutonic and mantle rocks, generally interpreted to represent pieces of oceanic crust and lithosphere

Ordovician the second period of the Paleozoic Era, falling between the Cambrian and the Silurian, commonly referred to as the age of marine invertebrates. The base of the Ordovician is defined on the Geological Society of America time scale (1999) as 505 million years ago, and the top or end of the Ordovician is defined at 438 million years ago.

orogenic belts linear chains of mountains, largely on the continents, that contain highly deformed, contorted rocks that represent places where lithospheric plates have collided or slid past one another

orogeny the process of building mountains

orographic effect the phenomenon occurring when clouds move over a mountain range and cool, which decreases the capacity of the air to hold water, resulting in precipitation falling on the windward side of the range. As the air mass moves down the leeward side of the mountain, it warms and is able to hold more moisture than is present, so the leeward sides of mountains tend to be dry.

ostracods shrimplike fossils belonging to the class Crustacea

outwash plain a broad plain in front of a melting glacier, where glacial streams deposit gravels and sand

overland flow the movement of runoff in broad sheets

oxbow lake an elongate and curved lake formed by an abandoned meandering stream channel on a floodplain

oxidize to remove one or more electrons from an atom, molecule, or ion, or at least to increase the proportion of the electronegative part of a compound. Weathering can be an oxidizing process, for instance, the oxidation of carbon to yield carbon dioxide.

ozone hole Ozone (O_3) is a poisonous gas that is present in trace amounts in much of the atmosphere, but reaches a maximum concentration in a stratospheric layer between 9 and 25 miles (15–40 km) above the Earth, with a peak at 15.5 miles (25 km). The presence of ozone in the stratosphere is essential for most life on Earth, since it absorbs the most carcinogenic part of the solar spectrum. Since the middle 1980s, a large hole marked by large depletions of ozone in the stratosphere has been observed above Antarctica every spring, its growth aided by the polar vortex circulation. The hole has continued to grow, but the relative contributions to the destruction of ozone by CFCs, other chemicals (such as supersonic jet and space shuttle fuel), volcanic gases, and natural fluctuations is uncertain.

paired metamorphic belt the name for a type of metamorphic pattern characteristic of convergent margin arcs, where rocks near the trench experience high-pressure/low temperature metamorphism, and the rocks near the magmatic arc experience high-temperature/low-pressure metamorphism

paleoclimatology the study of past and ancient climates, their distribution and variation in space and time, and the mechanisms of long term climate variations

Paleolithic the first division of the Stone Age in archeological time, marked by the first appearance of humans and their associated tools and workings. The time of the Paleolithic corresponds generally with the Pleistocene (from 1.8 million years ago until 10,000 years ago) of the geological time scale but varies somewhat from place to place.

paleomagnetism the study of the record of Earth's magnetic field as preserved in lava flows, volcanic rocks, and sedimentary rocks, and the use of these data to place constraints on plate tectonic motions

paleontology the study of past life based on fossil evidence, with a focus on the lines of descent of organisms and the relationships between life and other geologic phenomena

paleoseismicity the study of past earthquakes. Most paleoseismicity studies rely on techniques such as digging trenches across faults to determine the recurrence intervals of fault segments. Some paleoseismicity studies combine archeology with geology and look for ruins of ancient civilizations that show signs of earthquake damage, then use isotopic or historical dating methods to determine the time of the ancient destructive earthquake

Paleozoic the era of geologic time between 544 and 250 million years ago, including seven geological periods and systems of rocks: the Cambrian, Ordovician, Silurian, Devonian, Carboniferous (Mississippian and Pennsylvanian), and Permian

Pangaea a supercontinent that formed in the Late Paleozoic and held together from 300 to 200 million years ago. Pangaea contained most of the planet's continental land masses.

parallax the apparent displacement or difference in orientation of an object when viewed along two different lines of sight

parsec a distance that a star must lie so that its parallax is equal to 1 arc second, equivalent to 206,000 AU (one astronomical unit equals 1.496 $\times 10^8$ km), equivalent to 1.9×10^{13} miles, 3.09×10^{13} km, or 3.3 light years. A kiloparsec equals one thousand parsecs, a megaparsec equals one million parsecs, and a gigaparsec equals a billion parsecs, or 3.262 billion light-years, which is about one-fourteenth of the distance to the "horizon" of the presently observable universe.

partial melting the process in which a rock melts by only a small percentage, leaving mostly hot solid rock with a few (up to 10 or 20) percent liquid. These melts may stay in place, or move away to form larger magma bodies

passive continental margin a boundary between continental and oceanic crust that is not a plate boundary, characterized by thick deposits of sedimentary rocks. These margins typically have a flat, shallow-water shelf, then a steep drop off to deep ocean–floor rocks away from the continent.

pediments desert surfaces that slope away from the base of a highland and are covered by a thin or discontinuous layer of alluvium and rock fragments

pegmatite a coarse-grained igneous rock, typically composed of quartz, feldspar, mica, and other accessory minerals, sometimes gemstones. Most pegmatites are late-stage fluids associated with granitic plutons.

pelagic relating to the open sea, not along the shore or the bottom. Pelagic organisms are free-floating and do not need to be attached to the bottom or shoreline

pelite a clastic sedimentary rock with a grain size of less than 1/16 mm, including originally sandy or silty rocks

peneplain a nearly flat erosional plain produced by fluvial erosion, often recognized as a flat surface in uplifted mountain ranges

penumbra part of a shadow where the occulting body obscures only part of the light source

perched water table domed pockets of water at elevations higher than the main water table, resting on top of the impermeable layer

peridotite a common rock of the mantle of the Earth. The average upper mantle composition is equivalent to peridotite. The density of peridotite is 3.3 g/cm^3; its mineralogy includes olivine, clinopyroxene, and orthopyroxene.

perihelion the point in an orbit closest to the Sun

permafrost permanently frozen subsoil that occurs in polar regions and at some high altitudes

permeability a body's capacity to transmit fluids or to allow the fluids to move through its open pore spaces

Permian the last period in the Paleozoic era, lasting from 290–248 million years ago

petrography the science that describes the minerals and textures in rock bodies

petroleum a mixture of different types of hydrocarbons (fossil fuels) derived from the decomposed remains of plants and animals that are trapped in sediment, and which can be used as fuel

petrology the branch of geology that attempts to describe and understand the origin, occurrence, structure, and evolution of rocks

Phanerozoic the eon of geological time since the base of the Cambrian at 544 million years ago and extending to the present

phonon a quantized mode of vibration of a crystal lattice

photic zone zone through which light penetrates in the oceans

photoelectric effect a quantum electronic phenomenon where electrons are emitted from an object after it absorbs energy from electromagnetic radiation such as visible light or X-rays

photosphere the visible surface of the Sun

photosynthesis the process carried out in green plants, algae, and some bacteria that involves trapping solar energy and using it to drive a series of chemical reactions that result in the production of carbohydrates such as glucose or sugar

phylogeny the evolutionary history of an organism

pillow lava a form of lava flow with bulblike or pillowlike shapes, generally basaltic in composition, that forms beneath water and is common on the ocean floor

placer a deposit, typically found in streams, that contains high concentrations of gold (or another valuable mineral) in flakes or nuggets

plane strain a type of strain or deformation of a rock in which the rock is shortened in one direction, elongated in a perpendicular direction, and has no change in the third perpendicular direction

planet a celestial body that is in orbit around the Sun, has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and has cleared the neighborhood around its orbit

planetary nebula a type of emission nebula consisting of a glowing shell of gas and plasma surrounding a central core of a star that went through its hydrogen- and helium-burning stages, ejecting the outer layers of the dying giant star in one of the last stages of its evolution

planetesimal a protoplanet growing in the solar nebula

plasma a partially ionized gas in which some electrons are free rather than being bound to atoms or molecules

plate tectonics a model that describes the process related to the slow motions of more than a dozen rigid plates of solid rock around on the surface of the Earth. The plates ride on a deeper layer of partially molten material that is found at depths starting at 60–200 miles (100–320 km) beneath the surface of the continents, and 1–100 miles (1–160 km) beneath the oceans

playa a dry lake bed in a desert environment

Pleistocene the older of two epochs of the Quaternary Period, lasting from 1.8 million years ago until 10,000 years ago, at the beginning of the Holocene Epoch

Plinian a type of volcanic eruption characterized by a large and tall eruption column, typically reaching tens of thousands of feet (thousands of meters) into the air. Named after Pliny the Elder, from his description of Vesuvius

plume (radio galaxy) a relatively narrow trail of high-energy radiation emitted from a radio galaxy

Pluto The solar system has long been considered to have nine planets, with Pluto as the most-distant planet. In 2006 the International Astronomical Union met, decided that Pluto does not meet the formal criteria of being a planet, and demoted the status of the object to that of a "dwarf planet." Pluto is very small compared to all other planets, orbits far from the plane of the ecliptic, and resides in the Kuiper Belt, along with objects that are about the same order of magnitude in size and mass as Pluto. Pluto is thought to be composed of 98 percent nitrogen ice, along with methane and carbon monoxide, similar to other objects, including comets, in the Kuiper belt and in the scattered disk that overlaps with the outer edge of the Kuiper belt. If Pluto were to orbit close to the Sun, it would develop a long cometary tail, and would be classified as a comet, not a planet.

plutonic an igneous rock that has crystallized below the surface, typically characterized by coarse grain size and forming large intrusive bodies known as plutons

pluvial an extended period of abundant rainfall, particularly as applied to the Pleistocene epoch

podiform chromitite a concentration of chromite in a lens or pod, in an envelope or dike of dunite, in deformed mantle harzburgite tectonite. Podiform chromitites are typically found in ophiolites.

point bar deposits of sand and gravel along the inner bends of meandering streams

point defect a crystal defect in which something is wrong with the lattice at one point, such as an extra atom in one place, a missing atom at one place, or one atom substituting for another at one place

pole of rotation When a plate moves on the globe, its motion can be uniquely described by a rotation about a pole that goes through the center of the Earth, and exits at two places on the globe, known as poles of rotation.

polymorphs solids that have the same chemical formula but have different crystal lattice forms. Examples are carbon and diamond.

pore pressure In piles of sediments, the weight of the overlying material places the fluids under significant pore pressure, known as hydrostatic pressure, which keeps the pressure between individual grains in the regolith at a minimum. This in turn helps prevent the grains from becoming closely packed or compacted.

porosity the percentage of total volume of a body that consists of open spaces

positron the antiparticle, or antimatter counterpart, to the electron, containing an electric charge of +1 and the same mass as an electron. When a positron collides with an electron they annihilate each other, emitting two gamma ray photons.

Precambrian the oldest broad-grouping of geological time, stretching from the formation of the Earth at 4.5 billion years ago, including the Archean and Proterozoic eons, and ending at 540 million years ago

precipitation water that falls to the surface from the atmosphere in liquid, solid, or fluid form

prograding barriers barrier islands that are building themselves seaward with time, generally through a large sediment supply

prokaryote a single-celled organism lacking a cell nucleus, such as bacteria

Proterozoic the second eon of geological time, stretching from the end of the Archean eon at 2.5 billion years ago until the start of the Paleozoic at 540 million years ago

protoplanet a large body in the solar nebula that is in the process of growing by accretion into a planet

protosphere a surface on a star below which the material is opaque to the radiation it emits

pseudotachylytes glassy melt rocks that form along faults and from impact craters

pull-apart basin a rift-type basin formed along a bend in a strike-slip fault system or in an extensional area between two close and related strike-slip faults

pulsar strongly magnetized neutron stars that rotate with a regular period between a fraction of a second and 8.5 seconds, emitting a narrow beam of radio waves

pyroclastic a general term for rocks and material that are thrown from a volcano, including the explosive ash, bombs, and parts of the volcano ripped off the slopes during eruptions

quartzite a metamorphosed clean sandstone, in which fractures break through the individual grains as opposed to around them

quasar extremely powerful and distant galactic nucleus

Quaternary the last 1.8 million years of Earth history are known as the Quaternary period, divided into the older Pleistocene and the younger Holocene

radiation energy in the form of waves

radiative forcing the net change in downward minus the upward irradiance at the tropopause, caused by a change in an external driver such as a change in greenhouse gas concentration

radioactive decay the process whereby nuclei of unstable radioactive elements spontaneously break down to become more stable, emitting radiation as alpha particles, beta particles, or gamma rays

radio galaxies types of active galaxies that emit large amounts of electromagnetic radiation as radio waves

radiolarians small amoeboid protozoa that occur as free floating zooplankton in the open ocean, producing intricate exoskeletons that sink to form radiolarian ooze deposits on the sea floor. Many radiolarians make distinctive index fossils, so have been used to date marine stratigraphic units for much of the Phanerozoic.

radio waves electromagnetic waves with the longest wavelengths in the spectrum, between 1 mm and 100,000 km, commonly used to transport information through the atmosphere and space without wires

radon a heavy, poisonous gas produced as a product of radioactive decay in the uranium decay series. Radon presents a serious indoor health hazard in every part of the country.

rain shadow the area on the leeward side of a mountain where the air is descending, as a dry air mass, causing little rain to fall

rapakivi granite a hornblende-biotite granite with large rounded crystals of orthoclase feldspar surrounded by rims of oligoclase feldspar. Most rapakivi granites intruded orogens and cratons after the major deformation events, and are considered to be anorogenic.

recharge areas places where water enters the groundwater system

recumbent fold a flat-lying fold, with a subhorizontal axial plane and hinge

recurrence interval the average repeat time for earthquakes along a specific segment of a fault, based on the statistics of how frequently earthquakes of specific magnitude occur along individual segments of faults

recurved spit a sand spit that has ridges of sand that curve around the end of the spit that terminates in the sea, reflecting its growth

redshift a displacement of electromagnetic radiation emitted from a celestial body toward the lower energy red end of the visible spectrum, associated with an increase in the wavelength of the radiation since it was emitted. Redshifts are associated with objects moving away from the observer.

reef wave-resistant, framework-supported carbonate or organic mounds generally built by carbonate-secreting organisms; or, any shallow ridge of rock lying near the surface of the water

refraction the process of bending a wave front around an object, typically caused by friction on the base of the wave slowing its progress as it encounters shallow water, while parts of the wave still in deeper water continue to move quickly

regolith the outer surface layer of the Earth, consisting of a mixture of soil, organic material, and partially weathered bedrock

regression retreat of the sea from the shoreline, caused by eustatic sea-level fall or local effects

remote sensing the acquisition of information about an object by recording devices that are not in physical contact with the object. Different types include airborne or space-based techniques and sensors that measure different properties of earth materials, ground-based sensors that measure properties of distant objects, and techniques that penetrate the ground to map subsurface properties. Common use of the term *remote sensing* refers to the airborne and space-based observation systems, with ground-based systems more commonly referred to as geophysical techniques.

residence time average length of time that a substance remains in a geochemical system

resonances stable orbits where asteroids can remain for long periods of time, produced by an effect of the gravity and different orbital periods of the larger planets in the inner solar system. In physics, and in atmospheric and ocean dynamics, resonance can mean the tendency of a system to oscillate at a maximum amplitude at specific frequencies, known as the resonance frequencies for that system.

resonate oscillate back and forth. Many bodies have a specific rate or frequency at which they naturally resonate when excited with energy, known as a natural resonance. If a wave such as a tsunami excites the natural resonance of a harbor, then the height of a wave can be dramatically increased.

retrograding barriers barrier islands that are moving onshore with time

rhyolite an extrusive igneous rock that is the volcanic equivalent of granite, containing about 69 percent silicon dioxide (SiO_2), and typically containing the minerals quartz, alkali feldspar, and plagioclase

Richter scale an open-ended scale that gives an idea of the amount of energy released during an earthquake and is based on the amplitudes (half the height from wave-base to wave-crest) of seismic waves at a distance of 61 miles (100 km) from the epicenter. The Richter scale is logarithmic, where each step of 1 corresponds to a tenfold increase in amplitude. Because larger earthquakes produce more waves, an increase of 1 on the Richter scale corresponds to a 30-fold increase in energy released. Named after Frank Richter, an American seismologist

ridge and runnel the most seaward part of the beach, characterized by a small sandbar called a ridge, and a flat-bottom trough called the runnel, typically less than 30 feet (10 m) wide

rifts elongate topographic depressions, typically with faults along their margins, where the entire thickness of the lithosphere has ruptured in extension. These are places where the continents are beginning to break apart, and if successful, may form new ocean basins

rip current a strong current that moves perpendicularly away from the shore, typically localized by the presence of a jetty, sea floor topography, or other obstacle. Rip currents are dangerous as they can carry swimmers far out to sea.

river system the entire fluvial system, including all the tributaries of a river, its floodplain, water, and entrained and suspended sediment carried by the river

rockfall free falling of detached bodies of bedrock from a cliff or steep slope

rockslide the sudden downslope movement of newly detached masses of bedrock (or debris slides, if the rocks are mixed with other material or regolith)

Rossby waves dips and bends in the jet stream path

runoff water that fell as rain or snow and flows across the surface into streams or rivers, instead of being absorbed into the groundwater system

run-up the height of the tsunami above sea level at the farthest point it reaches on the shore

Saffir-Simpson scale a hurricane intensity scale that measures the damage potential of a storm, considering such factors as the central barometric pressure, maximum sustained wind speeds, and the potential height of the storm surge

saltation the movement of a particle by short intermittent jumps, such as caused by a water current lifting the particles

salt marshes coastal wetlands that form on the upper part of the intertidal zone where organic rich sediments are rarely disturbed by tides, providing a stable environment for grasses to take root. The low marsh area is defined as the part of the marsh that ranges from the beginning of vegetation to the least mean high tide. The high marsh extends from the mean high tide up to the limit of tidal influence.

sapping a process in which groundwater moves along the gravel and sand layers, seeping out along the river bank. This movement of groundwater can carry sediment away from the bank into the stream.

Saturn the sixth planet from the Sun, residing between Jupiter and Uranus, orbiting at 9.54 astronomical units (888 million miles, or 1,430 million kilometers) from the Sun, twice the distance from the center of the solar system as Jupiter, and with an orbital period of 29.5 Earth years. The mass of Saturn is 95 times that of Earth, yet it rotates at more than twice the rate of Earth.

schist medium-grade metamorphic rock that contains more than 50 percent platy and elongate minerals, aligned to produce a shiny luster. Most schists contain quartz, micas, and other accessory minerals such as garnet.

Schwarzschild radius a characteristic radius for a given mass at which, if the mass were compressed to fit inside that radius, no known force could stop the mass from collapsing to a singularity. It is also the radius for that mass at which no matter or energy could escape if the entire mass were compressed inside that radius.

seafloor spreading the process of producing new oceanic crust, as volcanic basalt pours out of the depths of the Earth, filling the gaps generated by diverging plates. Beneath the mid-oceanic ridges, magma rises from depth in the mantle and forms chambers filled with magma just below the crest of the ridges. The magma in these chambers erupts out through cracks in the roofs of the chambers, and forms extensive lava flows on the surface. As the two different plates on either side of the magma chamber move apart, these lava flows continuously fill in the gap between the diverging plates, creating new oceanic crust.

sea ice ice that has broken off an ice cap, from polar sea ice, or calved off a glacier and is floating in open water

sea-level rise the gradual increase in average height of the mean water mark with respect to the land

seasons variations in the average weather at different times of the year

sea stacks isolated columns of rock left by retreating cliffs, with the most famous being the Twelve Apostles along the southern coast of Australia

seawater intrusion the encroachment of seawater into drinking and irrigation wells, generally caused by overpumping of water from groundwater wells along the coast

sedimentary rock rocks that have consolidated from accumulations of loose sediment produced by physical, chemical, or biological processes

sedimentary structures the organized arrangement of sedimentary particles that form repeating patterns reflecting their origin. Types of sedimentary structures include sedimentary layers; ripples produced by currents moving the sedimentary particles as sets of small waves; megaripples, which are large ripples formed by unusually strong currents; mudcracks, produced by muddy sediments being dried by the Sun and shrinking and cracking; and other structures produced by organisms, such as burrows from worms, bivalves, and other organisms, trails, and footprints.

sediment flow a moving mass or deposit produced by mass-wasting processes that involve flows that are transitional between grain flows and stream-type flows in the relative amounts of sediment and water, and in velocity. Many different types of sediment flows include slurry flows, mudflows, debris flows, debris avalanches, earthflow, and loess flow.

seiche waves waves generated by the back-and-forth motion associated with earthquakes, causing a body of water (usually lakes or bays) to rock back and forth, gaining amplitude and splashing up to higher levels than normally associated with that body of water

seismic gaps places along large fault zones that have little or no seismic activity compared to adjacent parts of the same fault. Seismic gaps are generally interpreted as places where the fault zone is stuck, and where adjacent parts of the fault are gradually slipping along, slowly releasing seismic energy. Since the areas of the seismic gaps are not slipping, the energy gradually builds up in these sections, until it is released in a relatively large earthquake.

seismic reflection profile a geophysical cross section of part of the upper layers of the Earth produced by measuring the time it takes for a seismic wave (often artificially produced) to travel from the surface, bounce off a layer at depth, and travel back to the surface

seismic sea wave warning system a tsunami warning system in the Pacific Ocean that operates by monitoring seismograms to detect potentially seismogenic earthquakes, then monitors tide gauges to determine if a tsunami has been generated

seismograph a device built to measure the amount and direction of shaking associated with earthquakes

seismology the study of the propagation of seismic waves through the Earth, including analysis of earthquake sources, mechanisms, and the determination of the structure of the Earth through variations in the properties of seismic waves

sensitivity in soil, a measure of how the strength changes with shaking or with other disturbances such as those associated with excavation or construction

sequence stratigraphy the study of the large-scale three-dimensional arrangement of sedimentary strata and the factors that influence the geometry of these sedimentary packages. Sequences are groups of strata bounded above and below by identifiable surfaces that are at least partly unconformities.

shatter cone a group of fractures in a rock that forms a cone shape, and points towards the source of an explosion, such as a meteorite impact

shear waves *See* body waves.

sheeted dikes igneous dikes where each successive dike intrudes up the middle of the previously intruded dike, indicating intrusion in a region of extension, such as along a mid-ocean ridge

shrink/swell potential in soil, a measure of a soil's ability to add or lose water at a molecular level

Silurian the third period of Paleozoic time ranging from 443 Ma to 415 Ma, falling between the Ordovician and Devonian Periods. From base to top it is divided into the Llandoverian and Wenlockian ages or series (comprising the Early Silurian) and the Ludlovian and Pridolian ages or series (comprising the Late Silurian).

sinistral a term used to describe the sense of motion along a fault where the block on the opposite side of the fault moves to the left

sinkhole a large, generally circular depression that is caused by collapse of the surface into an underground open space

sinuosity ratio of the stream length to valley length

slaty cleavage a pervasive parallel foliation defined by fine-grained platy minerals such as chlorite

slickenside a smoothly polished surface marking a fault, typically containing striations or fibers oriented parallel to the movement direction on the fault

slides in mass wasting, when rock, soil, water, and debris move over and in contact with the underlying surface

slump a type of mass wasting where a large mass of rock or sediment moves downward and outward along an upward curving fault surface. Slumps may occur undersea or on the land surface.

slurry flow a moving mass of sediment saturated in water that is transported with the flowing mass. The mixture is so dense that it can suspend large boulders or roll them along the base.

SNC meteorites a class of meteorites that includes shergottites, nakhlites, and chassignites, believed to have originated from Mars and the Moon, being ejected by impact events on those planets, and landing on Earth

snowball Earth a time in Earth history when nearly all the water in the planet was frozen and glaciers existed at low latitudes

soil all the unconsolidated material resting above bedrock and serving as the natural medium for plant growth

soil profile a succession of distinctive horizons in a soil from the surface downward to unaltered bedrock

solar constant the amount of solar energy that reaches the Earth per unit time

solar luminosity a measure of the total energy emitted by the Sun, defined as the total energy reaching an imaginary sphere with a radius of 1 astronomical unit (AU, the distance from the Sun to the Earth)

solar mass the mass of the Sun, equivalent to 332,946 Earth masses, or 1.98892×10^{30} kg, commonly used as a standard reference to astronomical mass units

solar nebula the cloud of gases and solids in the early solar system from which the Sun and planets condensed and accreted

solar prominence a large bright feature that extends from the solar surface, often forming an arc-like shape

solar system The Earth's solar system represents the remnants of a solar nebula that formed in one of the spiral arms of the Milky Way Galaxy. After the condensation of the nebula, the solar system consisted of eight major planets, the moons of these planets, and many smaller bodies in interplanetary space. From the Sun outward, these planetary bodies include Mercury, Venus, Earth, Mars, the asteroids, Jupiter, Saturn, Uranus, and Neptune.

solifluction the slow viscous downslope movement of water-logged soil and debris. Solifluction is most common in polar latitudes where the top layer of permafrost melts, resulting in a water-saturated mixture resting on a frozen base.

solstice the time, occurring twice a year, when the Earth's axis is oriented the most toward or the most away from the Sun. The summer solstice happens on June 21 or 22, whereas the winter solstice happens every December 21 or December 22.

Spaceguard a term that refers to a number of different efforts to search for and monitor near-Earth objects

spectrum The electromagnetic spectrum is the range of all possible electromagnetic radiation. In astronomy, the word is typically used to refer to the spectrum of an object, such as a star, and in these cases refers to the characteristic distribution of electromagnetic radiation from that object.

spheroidal weathering a weathering process that proceeds along two or more sets of joints in the subsurface, resulting in shells of weathered rock which surround unaltered rocks, looking like boulders

spicules a several hundred mile (~500 km) diameter dynamic jet of material on the solar photosphere that shoots upward at 10–15 miles (~20 km) per second, and exists for only 5–10 minutes before fading away

spit a low tongue or embankment of land, typically consisting of sand and gravel, that terminates in the open water

springs places where groundwater flows out at the ground surface

spring tides tides that occur near the full and new Moons

stalactites pipelike formations that hang from the roof of a cave, formed by dripping water, typically composed of calcium carbonate

stalagmites pipelike formations that grow upward from the floor of caves, formed by accumulation of calcium carbonate from dripping water

standard model a model for the origin of the universe, stating that it formed 14 billion years ago in the big bang. This model suggests that galaxies and stars form 4.8 percent of the universe, 22.7 percent of the universe consists of dark matter, and 72.5 percent of the universe is nonmatter.

star a massive luminous ball of plasma in space

stony meteorites meteorites made of material typical of igneous rocks, such as minerals of olivine and pyroxene

stoping a mechanism of igneous intrusion whereby big blocks of country rock above a magma body get thermally shattered, drop off the top of the magma chamber, and fall into the chamber, and the magma then moves upward to take the place of the sunken blocks

storm beach thin strips of sand along a shoreline, formed typically in winter by strong winter storms that move sediment offshore from the beach

storm surge water that is pushed ahead of a storm and typically moves on land as an exceptionally high tide in front of a severe ocean storm such as a hurricane

stratigraphy the study of rock strata or layers, especially with concern for their succession, age relationships, lithologic composition, geometry, distribution, correlation, fossil content, and other aspects of the strata

stratosphere region of the atmosphere above the troposphere that continues to a height of about 31 miles (50 km)

stream capture an event that occurs when headland erosion diverts one stream and its drainage into another drainage basin

stream flow the flow of surface water in well-defined channels

strike-slip fault a vertical or nearly vertical fault that has horizontal or nearly horizontal motion along the fault

stromatolite a layered accretionary structure, formed by cyanobacteria, that traps, binds, and cements sedimentary grains, causing the structure to grow progressively outward from a starting nucleus

strong nuclear force one of the four basic forces in nature, responsible for holding the nucleus of atoms together, representing the interactions between quarks and gluons

structural geology the study of the deformation of the Earth's crust or lithosphere

subduction the destruction of oceanic crust and lithosphere by sinking back into the mantle at the deep ocean trenches. As the oceanic slabs go down, they experience higher temperatures that cause rock-melts or magmas to be generated, which then move upward to intrude the overlying plate. Since subduction zones are long narrow zones where large plates are being subducted into the mantle, the melting produces a long line of volcanoes above the down-going plate and forms a volcanic arc. Depending on what the overriding plate is made of, this arc may be built on either a continental or on an oceanic plate.

subduction erosion a process occurring at convergent margins in which material is eroded and scraped off the overriding plate and dragged down into the subduction zone

subduction zones long, narrow zones where large oceanic plates are sliding into the mantle. The down-going oceanic plates are associated with a zone of partial melting at about 60 miles (100 km) depth, generating magmas that rise to the surface, forming a long line of volcanoes above the down-going plate, and producing a volcanic arc. Depending on what the overriding plate is made of, this arc may be built on either a continental or on an oceanic plate.

subsequent stream a stream whose course has become adjusted so that it occupies a belt of weak rock or another geologic structure

subsidence sinking of one surface, such as the land, relative to another surface, such as sea level

Sun an average star, consisting of a glowing ball of gas held together by its own gravity and powered by nuclear fusion in its core, that sits 8 light minutes away from Earth

sun halos, sundogs, and sun pillars unusual optical phenomena related to the interaction of the Sun's rays with ice crystals in the upper atmosphere

supercontinent one large continent formed when plate tectonics and continental drift bring many or most of the planet's land masses into continuity. Examples of supercontinents include Pangaea that existed from about 300–200 million years ago and Gondwana that formed about 600 million years ago.

supercontinent cycle the semiregular grouping of the planet's landmasses into a single or several large continents that remain stable for a long period of time, then disperse, and eventually come back together as new amalgamated landmasses with a different distribution

supernova extremely luminous stellar explosion associated with large bursts of radiation that can exceed brightness of the entire galaxy it is associated with for a period of weeks or months

superposed streams streams whose courses were laid down in overlying strata onto unlike strata below

surface waves waves that travel along the surface, producing complicated types of twisting and circular motions, much like the circular motions exhibited by waves beyond the surf zone at the beach. Surface waves travel slower than either type of body waves, but they often cause the most damage due to their complicated types of motion.

suspended load the fine particles of silt and clay suspended in the stream that make it muddy and that move at the same or slightly lower velocity as the stream

suture zone a belt of highly deformed rocks in a modern or ancient mountain belt, typically containing fragments of ophiolites, mélanges, and blocks of high-grade metamorphic rock, marking the place where two continents or terranes have collided and an ocean has closed

swales the low areas in between dunes

synchrotron process the acceleration of charged particles to close to the speed of light in a magnetic field generating what is known as synchrotron radiation, governed by relativistic effects described by quantum mechanics

syncline a fold structure in which the associated beds dip inward and the youngest rocks occupy the core of the fold structure

synclinorium a large, regional-scale syncline that may have smaller-scale anticlines and synclines superimposed on the larger-scale structure

talus the entire body of rock waste sloping away from the mountains. The sediment composing talus is known as sliderock. This rock debris accumulates at the bases of mountain slopes, deposited there by rockfalls, rockslides, and other downslope movements

tectosphere the region of the Earth's crust occupied by tectonic plates

telescope any of a wide range of scientific instruments that observe remote objects by collecting electromagnetic radiation from them and enhancing this radiation by different processes in different types of telescopes

tephra a general term for all ash and rock fragments strewn from a volcano

terrace flat abandoned floodplain, sitting above the present floodplain level, that formed when a stream flowed above its present channel and floodplain level

terrane a fault-bounded block of rock that has a geologic history different from that of neighboring rocks, and likely was transported from far away by plate tectonic processes

Tertiary the first period of the Cenozoic era, extending from the end of the Cretaceous of the Mesozoic at 66 million years ago until the beginning of the Quaternary 1.6 million years ago. The Tertiary is divided into two periods, the older Paleogene (66–23.8 Ma) and the younger Neogene (23.8–1.8 Ma), and further divided into five epochs, the Paleocene (66–54.8 Ma), Eocene (54.8–33.7 Ma), Oligocene (38.7–23.8 Ma), Miocene (23.8–5.3 Ma), and Pliocene (5.3–1.6 Ma).

thalweg a line connecting the deepest parts of the channel of a stream or river

thermodynamics the study of the transformation of heat into and from other forms of energy, particularly mechanical, chemical, and electrical energy

thermohaline circulation vertical mixing of seawater driven by density differences caused by variations in temperature and salinity

thermosphere region of the atmosphere above the mesosphere that thins upward and extends to about 311 miles (500 km) above the surface

thixotropic a property of material such as mud that causes it to be fairly rigid when it is held or is still, but when it is shaken or disturbed, it rapidly turns into a fluid

tholeiitic relating to igneous rock dominated by plagioclase, and chemically containing less alkali elements (Na_2O plus K_2O) at similar SiO_2 than alkali basalt

thrust a contractional fault, or a reverse fault generally with shallow dips

thunderstorms convective storm systems that contain lightning and thunder and that form in unstable rising warm and humid air currents

tidal bore a breaking wave that migrates up the bay as the tide floods the bay, formed where the shape of the bay constricts the water flow, causing the wave to grow in height as it moves into smaller and smaller areas

tidal flat a flat area along the coast within the tidal range that is sheltered from waves, dominated by mud, devoid of vegetation, and accumulating sediment

tidal gauge a sensitive pressure meter placed on the seafloor that can accurately measure changes in the height of the sea surface and can be used for the detection of tides, storm surges, and tsunamis

tidal inlet break in barrier island system that allows water, nutrients, organisms, ships, and people easy access and exchange between the high-energy open ocean and the low-energy back-barrier environment consisting of bays, lagoons, tidal marshes, and creeks. Most tidal inlets are within barrier island systems, but others may separate barrier islands from rocky or glacial headlands.

tidal range the range in sea surface height between the high and low tide

tides the periodic rise and fall of the ocean surface, and alternate submersion and exposure of the intertidal zone along coasts

tidewater glaciers glaciers that are partly floating on the ocean, often in steep-walled fjords

till glacial drift that was deposited directly by the ice

tilt an astronomical measure of how much the Earth's rotational axis is inclined relative to the perpendicular to the plane of orbit

tombolo a spit that connects an offshore island with the mainland

tonalite an igneous rock that is similar to granite but is composed of the minerals plagioclase and quartz plus minor dark minerals such as amphibole, pyroxene, or biotite

tornado a rapidly circulating column of air with a central zone of intense low pressure that reaches the ground

trace fossil geological record of biological activity, such as footprints, worm burrows, or other markings preserved as fossils

transform boundaries places where two tectonic plates slide past each other, such as along the San Andreas fault in California, that often experience large earthquakes

transgression advance of the sea on the shore, caused by either a eustatic sea level rise or local effects

translational slide a variation of a slump in which the sliding mass moves not on a curved surface, but moves downslope on a preexisting plane, such as a weak bedding plane or a joint. Translational slides may remain relatively coherent or break into small blocks, forming a debris slide.

transmissivity the ability of a substance to allow water to move through it

transpiration the evaporation of water from the exposed parts of plants

trellis drainage parallel mainstream channels intersected at nearly right angles by tributaries

triple junction places where three plate boundaries meet

trondhjemite a light-colored intrusive igneous rock, consisting of plagioclase and quartz, common in the sheeted dike sections of ophiolites and in Archean greenstone belts

troposphere the lower 36,000 feet (10,972.8 m) of the atmosphere

tsunami a giant harbor or deepwater wave with long wavelengths, initiated by submarine landslides, earthquakes, volcanic eruptions, or another cause, that suddenly displaces large amounts of water. Tsunamis can be much larger than normal waves when they strike the shore, and they can cause great damage and destruction.

tsunami earthquakes a special category of earthquakes that generate tsunamis that are unusually large for the earthquake's magnitude

T-Tauri stage a stage of stellar evolution where a young (< 10 million years old) small star, less than three solar masses, is still undergoing gravitational contraction. This is an intermediate stage in stellar evolution between a protostar and a main sequence star (such as the Sun).

tube worm marine invertebrate belonging to the phylum Annelida. Tube worms are found near hot springs on the ocean floor. Some of these are thermophilic (heat-loving) and all are primitive organisms.

tuff a rock comprised of a cooled and crystallized volcanic ash, characterized by fine grain size and commonly having fine-scale layers and indications of high-temperature flow

turbidite a sedimentary unit characterized by being deposited by a turbidity current. Most turbidites show a sequence of coarse-grained sands at their base and fine silts or mud on their tops, indicting deposition during slowing of the current.

turbidity current subaqueous downslope flow of water-saturated sand and mud, that leaves behind a turbidite deposit of graded sand and shale

turbulent flow in a flowing stream, water that moves in different directions and often forms zones of sideways or short backward flows called eddies. These significantly increase the resistance to flow. In turbulent flows, the resistance is proportional to the square of the flow velocity.

ultramafic relating to dark-colored igneous rocks composed of iron-magnesium minerals, with silica content of less than 45 percent as determined by chemical analysis. Some ultramafic igneous rocks include peridotite and komatiite.

umbra the darkest part of a shadow, where the source of light is completely obscured by the occulting body

unconformity a buried erosion surface that separates two rock masses of different ages. Angular unconformities form when a deformation and tilting event separates the deposition of the two rock groups, nonconformities represent nondeposition, and disconformities form where a young rock sequence is deposited on an older igneous or metamorphic terrane.

underseepage the process of water seeping under a levee or other structure, often resulting in catastrophic failure of the levee

universe all matter and energy everywhere, including the Earth, solar system, galaxies, interstellar matter and space, regarded as a whole

Uranus the seventh planet from the Sun. Uranus is a giant gaseous sphere with a mass 15 times that of the Earth and a diameter four times as large as Earth's (51,100 km). The equatorial plane is circled by a system of rings, some associated with the smaller of the 15 known moons circling the planet. Uranus orbits the Sun at a distance of 19.2 astronomical units (Earth-Sun distance) with a period of 84 Earth years and has a retrograde rotation of 0.69 Earth days. Its density is only 1.2 grams per cubic centimeter.

urban heat island an effect where cities tend to hold heat more than the countryside

urbanization the process of building up and populating a natural habitat or environment, such that the habitat or environment no longer responds to input the way it did before being altered by humans

Vendian the last period of the Proterozoic in the Precambrian, lasting from 650–543 million years ago. The Vendian has a wonderful soft-bodied faunal assemblage preserved in it, but many of these organisms died off before the Phanerozoic era began.

Venus the second planet from the Sun. Venus has a planetary radius of 3,761 miles (6,053 km), or 95 percent of that of Earth's radius, orbits the Sun in a nearly circular path at 0.72 astronomical units (Earth-Sun distance), has a mass equal to 81 percent of Earth's, and has density of 5.2 grams per cubic centimeter.

vicariance biogeography the initially wide distribution of primitive groups that later were broken up by processes such as rifting and divergent plate tectonics, leading to evolution in individual isolated groups

viscosity a measure of the resistance to flow. The more viscous a fluid is, the more resistant it is to flow.

volcanic arc a line of volcanoes that forms above a subducting oceanic plate at a convergent boundary; *See also* magmatic arc.

volcano a mountain or other constructive landform built by a singular or a sequence of volcanic eruptions of molten lava and pyroclastic material from a volcanic vent

wadi a dry stream bed. This term is commonly used in Arabic countries.

water resources any sources of water that are potentially available for human use, including lakes, rivers, rainfall, reservoirs, and the groundwater system

water table the boundary between the saturated and unsaturated zones

wave base the depth at which all motion associated with the passage of the wave stops, and the water beneath this point experiences no effect from the passage of the wave above. In deepwater ocean waves, the particle motion follows roughly circular paths, where particles move approximately in a circle, and return back to their starting position after the wave passes. The amount of circular motion decreases gradually with depth, to a depth that equals one-half of the wavelength, where all motion associated with the wave passage stops.

wave fronts imaginary lines drawn parallel to the wave crests. A wave moves perpendicular to the wave fronts.

wave height the vertical distance from the crest to the bottom of the trough of a wave

wavelength the distance between successive troughs or crests on a wave train

wave period the time (in seconds) that it takes successive wave crests to pass a point

wave refraction a phenomenon that occurs when a straight wave front approaches a shoreline obliquely. The part of the wave front that first feels shallow water (with a depth of less than one half of the wavelength, known as the wave base) begins to slow down while the rest of the wave continues at its previous velocity. This causes the wave front to bend, or be refracted.

wave train waves of a certain character in a series, moving across the ocean or body of water

wave trap areas such as some bays and other places along some shorelines that amplify the effects of waves coming in from a certain direction, making run-ups higher than average

weathering the process of mechanical and chemical alteration marked by the interaction of the lithosphere, atmosphere, hydrosphere, and biosphere

welded barriers barrier islands that have grown completely across a bay and sealed the water inside off from the ocean

Widmanstaetten texture a criss-cross texture best shown on polished metallic surfaces of iron meteorites, produced by intergrown blades of iron and nickel minerals, with the size of the blades related to the cooling rate of the minerals

windward the side of a mountain facing the oncoming prevailing winds, typically the wet side of a mountain range

wobble an astronomical measure of the rotation axis describing a motion much like a top's rapidly spinning and rotating with a wobbling motion, such that the direction of tilt toward or away from the Sun changes, even though the tilt amount stays the same. This wobbling phenomenon is known as precession of the equinoxes.

xenolith a piece of rock, typically derived from the mantle, caught and preserved in a crystallized magma or in a kimberlite pipe

yardangs elongate streamlined wind-eroded ridges that resemble an overturned ship's hull sticking out of the water

zero-age main sequence the time at which the stellar properties of an young star become stable and the star enters a steady period of burning or fusion

Appendix III
Further Resources

BOOKS

Abbott, Patrick L. *Natural Disasters*. 3rd ed. Boston: McGraw-Hill, 2002. A college freshman–level book about natural disasters, listing causes and examples.

Abrahams, A. D., and A. J. Parsons. *Geomorphology of Desert Environments*. Norwell, Massachusetts: Kluwer Academic Publishers for Chapman and Hall, 1994. This is a comprehensive textbook, describing the wide range of landforms and processes in desert environments.

Ahrens, C. D. *Meteorology Today, An Introduction to Weather, Climate, and the Environment*. 7th ed. Pacific Grove, Calif.: Brooks/Cole, 2003. An introductory text for freshman college levels on meteorology, weather, and climate.

Alley, W. M., T. E. Reilly, and O. L. Franke. *Sustainability of Ground-Water Resources*. United States Geological Survey Circular 1186, 1999. This book discusses the use and misuse of groundwater, including the effects of contamination and pollution.

Angelo, Joseph A. *Encyclopedia of Space and Astronomy*. New York: Facts On File, 2006. This is a comprehensive, high school–to-college level encyclopedia covering thousands of topics in astronomy.

Armstrong, B. R., and K. Williams. *The Avalanche Book*. Armstrong, Colo.: Fulcrum Publishing, 1992. This is a comprehensive yet readable book about avalanches and their hazards.

Ashworth, William, and Charles E. Little. *Encyclopedia of Environmental Studies*. New Ed. New York: Facts On File, 2001. A comprehensive encyclopedia for high school students covering diverse aspects of the environment.

Ball, Philip. *The Elements: A Very Short Introduction*. New York: Oxford University Press, 2005. A simple introduction to each of the groups of chemical elements.

Birkland, P. W. *Soils and Geomorphology*. New York: Oxford University Press, 1984. This is a general, college-level textbook on soil science and geomorphology.

Blong, Russell J. *Volcanic Hazards, A Sourcebook on the Effects of Eruptions*. New York: Academic Press, 1984. This book discusses the geological hazards associated with volcanic eruptions.

Botkin, D., and E. Keller. *Environmental Science*. Hoboken, N.J.: John Wiley and Sons, 2003. This is an introductory college-level book that discusses many issues of environmental sciences.

Bromley, D. Allan. *A Century of Physics*. New York: Springer, 2002. A tour from the last century of physics growth, impact, and directions. Numerous photos and illustrations.

Chaisson, Eric, and Steve McMillan. *Astronomy Today*. 2nd ed. Upper Saddle River, N.J.: 2007. A college-level textbook on astronomy.

Chapple, Michael. *Schaum's A to Z Physics*. New York: McGraw-Hill, 2003. Defines 650 key concepts with diagrams and graphs, intended for high school students and college freshmen.

Charap, John M. *Explaining the Universe: The New Age of Physics*. Princeton, N.J.: Princeton University Press, 2002. A description of the field of physics at the beginning of the 21st century.

Considine, Glenn D., ed. *Van Nostrand's Scientific Encyclopedia*. 10th ed. 3 vols. New York: John Wiley & Sons, 2008. Comprehensive general reference containing more than 10,000 entries on topics ranging from all scientific disciplines including the life sciences, Earth and atmospheric sciences, physical sciences, medicine, and mathematics, as well as many areas of engineering and technology.

Davis, R., and D. Fitzgerald. *Beaches and Coasts*. Malden, Mass.: Blackwell Publishing, 2004. This is a comprehensive, undergraduate-to-graduate–level text on processes and environments on beaches and coasts.

Dawson, A. G. *Ice Age Earth,* London: Routledge, 1992. This book describes environmental and geological conditions on the Pleistocene Earth during the ice ages.

Dennis, Johnnie T. *The Complete Idiot's Guide to Physics*. Indianapolis, Ind.: Alpha Books, 2003.

A friendly review of high school–level classical physics.

Dewick, Paul M. *Essentials of Organic Chemistry*. Hoboken, N.J.: John Wiley & Sons, 2006. An introductory textbook of organic chemistry.

The Diagram Group. *The Facts On File Physics Handbook*. Rev. ed. New York: Facts On File, 2006. Convenient resource containing a glossary of terms, short biographical profiles of celebrated physicists, a chronology of events and discoveries, and useful charts, tables, and diagrams.

Drew, D. *Karst Processes and Landforms*. New York: MacMillan Education Press, 1985. This is a comprehensive review of the geological conditions that lead to the development of karst terrains.

Elkins-Tanton, Linda T. *Asteroids, Meteorites, and Comets*. New York: Facts On File, 2006. This is a good high school book that covers the characteristics, formation, and evolution of asteroids, meteorites, and comets.

Falk, Dan. *Universe on a T-Shirt: The Quest for the Theory of Everything*. New York: Arcade Publishing, 2002. A story outlining developments in the search for the theory that will unify all four natural forces.

Fleisher, Paul. *Relativity and Quantum Mechanics: Principles of Modern Physics*. Minneapolis, Minn.: Lerner Publications, 2002. An introduction to the concepts of relativity and quantum mechanics, written for middle school students.

Francis, Peter. *Volcanoes, A Planetary Perspective*. Oxford, England: Oxford University Press, 1993. This book discusses the role of volcanoes in planetary processes such as magma budget, lithosphere-asthenosphere interactions, and variations among volcanoes on the planet.

Gillispie, Charles C., ed. *Dictionary of Scientific Biography*. 18 vols. New York: Charles Scribner's Sons, 1970–81. *New Dictionary of Scientific Biography*. 8 additional vols., 2007. More than 5,000 biographies of scientists and mathematicians from around the world.

Gordon, N. D., T. A. McMahon, and B. L. Finlayson. *Stream Hydrology—an Introduction for Ecologists*. New York: John Wiley and Sons, 1992. This is an elementary book for non-specialists on the hydrology and dynamics of streams.

Griffith, W. Thomas. *The Physics of Everyday Phenomena*. 4th ed. Boston: WCB/McGraw-Hill, 2004. A conceptual text for nonscience college students.

Hamblin, Jacob Darwin. *Science in the Early Twentieth Century: An Encyclopedia*. Santa Barbara, Calif.: ABC-CLIO, 2005. Alphabetical entries examining science from 1900–50.

Holton, Gerald James, and Stephen G. Brush. *Physics, the Human Adventure: From Copernicus to Einstein and Beyond*. New Brunswick, N.J.: Rutgers University Press, 2001. Comprehensive introduction intended for nonscience college students. Difficult reading but covers a lot of material.

Intergovernmental Panel on Climate Change. *Climate Change 2007: The Physical Science Basis. Contributions of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller. Cambridge: Cambridge University Press, 2007. This is the most comprehensive and up-to-date scientific assessment of past, present, and future climate change.

Intergovernmental Panel on Climate Change. *Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contributions of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* edited by M. Parry, O. Canziani, J. Palutikof, P. van der Linden, and C. Hanson. Cambridge: Cambridge University Press, 2007. This is the most comprehensive and up-to-date scientific assessment of the impacts of climate change, the vulnerability of natural and human environments, and the potential for response through adaptation.

Intergovernmental Panel on Climate Change. *Climate Change 2007: Mitigation. Contributions of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* edited by B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, and L. A. Meyer. Cambridge: Cambridge University Press, 2007. This is the most comprehensive and up-to-date assessment of mitigation of future climate change.

Interrante, Leonard V., Lawrence A. Casper, and Arthur B. Ellis. *Materials Chemistry: An Emerging Discipline*. Washington, D.C.: American Chemical Society, 1995. A college-level introduction to material science.

James, Ioan. *Remarkable Physicists: From Galileo to Yukawa*. New York: Cambridge University Press, 2004. Contains brief biographies of 50 physicists spanning a period of 250 years, focusing on the lives rather than the science.

Kusky, T. M. *Asteroids and Meteorites: Catastrophic Collisions with Earth, The Hazardous Earth Set*. New York: Facts On File, 2009. A comprehensive account of asteroids, meteorites, and the effects of their collisions with Earth, illustrated with many examples for high school and college students.

———. *Climate Change: Shifting Glaciers, Deserts, and Climate Belts, The Hazardous Earth Set*.

New York: Facts On File, 2008. A comprehensive account of short-, medium-, and long-term climate change and what drives changes in climate, illustrated with many examples for high school and college students.

———. *The Coast: Hazardous Interactions within the Coastal Environment, The Hazardous Earth Set*. New York: Facts On File, 2008. A comprehensive account of hurricanes, coastal erosion, land subsidence, and rising sea levels, illustrated with many examples for high school and college students.

———. *Earthquakes: Plate Tectonics and Earthquake Hazards, The Hazardous Earth Set*. New York: Facts on File, 2008. A comprehensive account of earthquakes and their causes, illustrated with many examples for high school and college students.

———. *Encyclopedia of Earth and Space Science*. 2 vols. New York: Facts On File, 2009. Contains more than 200 entries on topics related to the NSES content standards for grades 9–12, a chronology, glossary, and further resources.

———. *Floods: Hazards of Surface and Groundwater Systems, The Hazardous Earth Set*. New York: Facts On File, 2008. A comprehensive account of the Earth's hydrosphere, including floods, groundwater contamination, and other water issues, illustrated with many examples for high school and college students.

———. *Geologic Hazards, A Sourcebook*. Westport, Conn.: Greenwood Press, 2002.

———. *Landslides: Mass Wasting, Soil, and Mineral Hazards, The Hazardous Earth Set*. New York: Facts On File, 2008. A comprehensive account of landslides and hazards including contaminants in soils, illustrated with many examples for high school and college students.

———. *Tsunamis: Giant Waves from the Sea, The Hazardous Earth Set*. New York: Facts On File, 2008. A comprehensive account of tsunamis, including the 2004 Indian Ocean tsunami, illustrated with many examples for high school and college students.

———. *Volcanoes: Eruptions and Other Volcanic Hazards, The Hazardous Earth Set*. New York: Facts On File, 2008. A comprehensive account of volcanic eruptions and their consequences, illustrated with many examples for high school and college students.

Leiter, Darryl J. *A to Z of Physicists*. New York: Facts On File, 2003. Profiles more than 150 physicists, discussing their research and contributions. Includes bibliography, cross-references, and chronology.

Leopold, L. B. *A View of the River*. Cambridge, Mass.: Harvard University Press, 1994. This is a layman's description of river systems.

Lerner, K. Lee, and Brenda Wilmoth Lerner, eds. *Gale Encyclopedia of Science*. 4th ed. 6 vols. Farmington Hills, Mich.: Gale Group, 2007. Provides an overview of current knowledge in all major areas of science, engineering, technology, mathematics, and the medical and health sciences, consisting of alphabetical entries of scientific concepts and terms.

Longshore, D. *Encyclopedia of Hurricanes, Typhoons, and Cyclones*. New Ed. New York: Facts On File, 1998. A comprehensive encyclopedia of hurricanes written for college and high school audiences and the general public.

Nemeh, Katherine H., ed. *American Men and Women of Science: A Biographical Dictionary of Today's Leaders in Physical, Biological, and Related Sciences*. 25th ed. 8 vols. Farmington Hills, Mich.: Thomson Gale, 2008. Brief profiles of nearly 135,000 living scientists.

Oakes, Elizabeth H. *Encyclopedia of World Scientists*. Rev. ed. 2 vols. New York: Facts On File, 2007. Profiles nearly 1,000 scientists from around the world.

Ritter, D. F., R. C. Kochel, and J. R. Miller. *Process Geomorphology*. 3rd ed. Dubuque, Iowa: W.C. Brown, 1995. This is a comprehensive book describing modern views on geomorphology and river system dynamics.

Rosen, Joe, and Lisa Q. Gothard. *Encyclopedia of Physical Science*. 2 vols. New York: Facts On File, 2009. Contains more than 200 entries on topics related to the NSES content standards for grades 9–12, a chronology, glossary, and further resources.

Trefil, James. *From Atoms to Quarks: An Introduction to the Strange World of Particle Physics*. Rev. ed. New York: Anchor Books, 1994. A primer on this complex subject written for general readers.

United States Environmental Protection Agency and Centers for Disease Control. *A Citizen's Guide to Radon: The Guide to Protecting Yourself and Your Family from Radon*. 2nd ed. EPA 402-K92-001, 1992. A general interest booklet on how to check for and reduce the risk of radon in homes and the environment.

INTERNET RESOURCES

The ABCs of Nuclear Science. Nuclear Science Division, Lawrence Berkeley National Laboratory. Available online. URL: http://www.lbl.gov/abc/. Accessed July 22, 2008. Introduces the basics of nuclear science—nuclear structure, radioactivity, cosmic rays, antimatter, and more.

American Chemical Society. Available online. URL: http://portal.acs.org/portal/acs/corg/content. Accessed July 22, 2008. Home page of ACS. Includes useful resources under education and information about new areas in chemistry.

American Geological Institute Government Affairs Program. Available online. URL: http://www.agiweb.org/gap/index.html. Accessed February 4, 2009. The AGI Government Affairs Program (GAP), established in 1992, serves as an important link between the federal government and the geoscience community. Through Congressional workshops, testimony, letters, and meetings, GAP ensures that the voices of the AGI Member Societies are heard on Capitol Hill and in the executive branch. At the same time, GAP is working to improve the flow of geoscience information to policy-makers. Equally important is the program's mission of providing federal science-policy information back to the member societies and the geoscience community at large.

American Institute of Physics: Center for History of Physics. AIP, 2004. Available online. URL: http://www.aip.org/history/. Accessed July 22, 2008. Visit the "Exhibit Hall" to learn about events such as the discovery of the electron or read selected papers of great American physicists.

American Museum of Natural History home page. Available online. URL: http://www.amnh.org/. Accessed February 6, 2008. Contains links for research conducted by the museum, and updates on scientific topics.

American Physical Society. A Century of Physics. Available online. URL: http://timeline.aps.org/. Accessed July 22, 2008. Wonderful, interactive timeline describing major events in the development of modern physics.

———. Physics Central. Available online. URL: http://www.physicscentral.com/. Accessed July 22, 2008. Updated daily with information on physics in the news, current research, and people in physics.

Astronomy Today. Available online. URL: http://www.astronomytoday.com/. Accessed February 5, 2009. Web site on news and interesting topics in astronomy.

Dinosaur Extinction Page. Available online. URL: http://web.ukonline.co.uk/a.buckley/dino.htm Accessed February 4, 2009. Web site offers short summaries of some theories of dinosaur extinction, including meteorite impacts and volcanic eruptions.

Fear of Physics. Available online. URL: http://www.fearofphysics.com/. Accessed July 22, 2008. Entertaining way to review physics concepts.

Federal Emergency Management Agency. Available online. URL: http://www.fema.gov. Accessed February 4, 2009. FEMA is the nation's premier agency that deals with emergency management and preparation and issues warnings and evacuation orders when disasters appear imminent. FEMA maintains a Web site that is updated at least daily, including information on hurricanes, floods, fires, national flood insurance, and information on disaster prevention, preparation, and emergency management. Divided into national and regional sites. Also contains information on costs of disasters, maps, and directions on how to do business with FEMA. FEMA, 500 C Street, SW, Washington, D.C. 20472.

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also participate in the review of IPCC Reports. The IPCC includes hundreds of scientists from all over the world who contribute to the work of the IPCC as authors, contributors, and reviewers. As a United Nations body, the IPCC aims at the promotion of the United Nations human development goals. The IPCC was established to provide the decision makers and others interested in climate change with an objective source of information about climate change. The IPCC does not conduct any research nor does it monitor climate-related data or parameters. Its role is to assess on a comprehensive, objective, open and transparent basis the latest scientific, technical and socioeconomic literature produced worldwide relevant to the understanding of the risk of human-induced climate change, its observed and projected impacts, and options for adaptation and mitigation. IPCC reports should be neutral with respect to policy, although they need to deal objectively with policy-relevant scientific, technical, and socioeconomic factors. They should be of high scientific and technical standards and aim to reflect a range of views, expertise, and wide geographical coverage.

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National Aeronautical and Space Administration (NASA). Near-Earth Object Program. Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, California 91109, (818) 354-4321. Available Online. URL: http://neo.jpl.nasa.gov/. Accessed February 4, 2009. In 1998 NASA initiated a program called the "Near-Earth Object Program," whose aim is to catalog potentially hazardous asteroids that could present a hazard to Earth. This program uses five large telescopes to search the skies for asteroids that pose a threat to Earth and to calculate their mass and orbits. So far, the largest potential threat known is from asteroid 99AN10, which has a mass of 2.2 billion tons and may pass within the orbit of the moon, at 7:10 A.M., August 7, 2027. NASA has another related program called "Deep Impact," designed to collect data on the composition of a comet named Tempel 1, which will be passing beyond the orbit of Mars. The comet is roughly the size of mid-town Manhattan, and the spacecraft will be shooting an object at the comet to determine its density by observing the characteristics of the impact.

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Lawrence Berkeley National Laboratory, 2002. Available online. URL: http://particleadventure.org/. Accessed July 22, 2008. Interactive tour of quarks, neutrinos, antimatter, extra dimensions, dark matter, accelerators, and particle detectors.

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U.S. Geological Survey. Available online. URL: U.S. Department of the Interior, 345 Middlefield Road, Menlo Park, CA 94025; also, offices in Reston, Virginia, and Denver, Colorado; Main Offices URL: http://www.usgs.gov. Accessed February 4, 2009. Earthquake Hazards Program monitors recent earthquakes worldwide. The USGS is responsible for making maps of many of the different types of earthquake hazards discussed in this book, including earthquake-related shaking hazards, tsunamis, landslides, and others. This site also provides answers to frequently asked questions about earthquakes URL: http://earthquake.usgs.gov/. Accessed February 4, 2009. U.S. Geological Survey, National Earthquake Information Center, Federal Center, Box 25046, MS 967, Denver, CO 80225-0046, U.S.A.

Volcanoworld. Available online. URL: http://volcano.oregonstate.edu/. Accessed February 4, 2009. Presents updated information about eruptions and volcanoes and has many interactive pages designed for different grade levels from kindergarten through college and professional levels. Volcanoworld is an award-winning Web site, designed as a collaborative Higher Education, K-12, and Public Outreach project of the North Dakota and Oregon Space Grant Consortia administered by the Department of Geosciences at Oregon State University.

Windows to the Universe team. Fundamental Physics. Boulder, Colo.: ©2000–04 University Corporation of Atmospheric Research (UCAR), ©1995–99, 2000 The Regents of the University of Michigan. Available online. URL: http://www.windows.ucar.edu/tour/link=/physical_science/physics/physics.html. Accessed July 22, 2008. Still under construction, this site will contain a broad overview of physics and already has many links to physics topics including mechanics, electricity and magnetism, thermal physics, and atomic and particle physics.

PERIODICALS

The American Naturalist
Published for the American Society of Naturalists by The University of Chicago Press
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SOCIETIES AND ORGANIZATIONS

American Association for the Advancement of Science (www.aaas.org), 1200 New York Avenue N.W., Washington, DC 20005. Telephone: (202) 326-6400

American Chemical Society (www.acs.org), 1155 16th Street N.W., Washington, DC 20036. Telephone: (202) 872-4600

American Geological Institute (http://www.agiweb.org/), 4220 King Street, Alexandria, VA 22302-1502. Telephone: (703) 379-2480

American Geophysical Union (http://www.agu.org/), 2000 Florida Avenue N.W., Washington, DC 20009-1277. Telephone: (202) 462-6900

American Physical Society (www.aps.org), One Physics Ellipse, College Park, MD 20740-3844. Telephone: (301) 209-3200

Geological Society of America (http://www.geosociety.org/), P.O. Box 9140, Boulder, CO 80301-9140. Telephone: (303) 357-1000

The Minerals, Metals, & Materials Society (www.tms.org), 184 Thorn Hill Road, Warrendale, PA 15086-7514. Telephone: (724) 776-9000

National Science Foundation (www.nsf.gov), 4201 Wilson Boulevard, Arlington, VA 22230. Telephone: (703) 292-5111; FIRS: (800) 877-8339; TDD: (800) 281-8749

Society of Physics Students (www.spsnational.org), American Institute of Physics, One Physics Ellipse, College Park, MD 20740-3843. Telephone: (301) 209-3007

Woods Hole Oceanographic Institute (http://www.whoi.edu/), 266 Woods Hole Road, Woods Hole, MA 02543. Telephone: (508) 289-2252. WHOI is the world's largest private, nonprofit ocean research, engineering, and education organization.

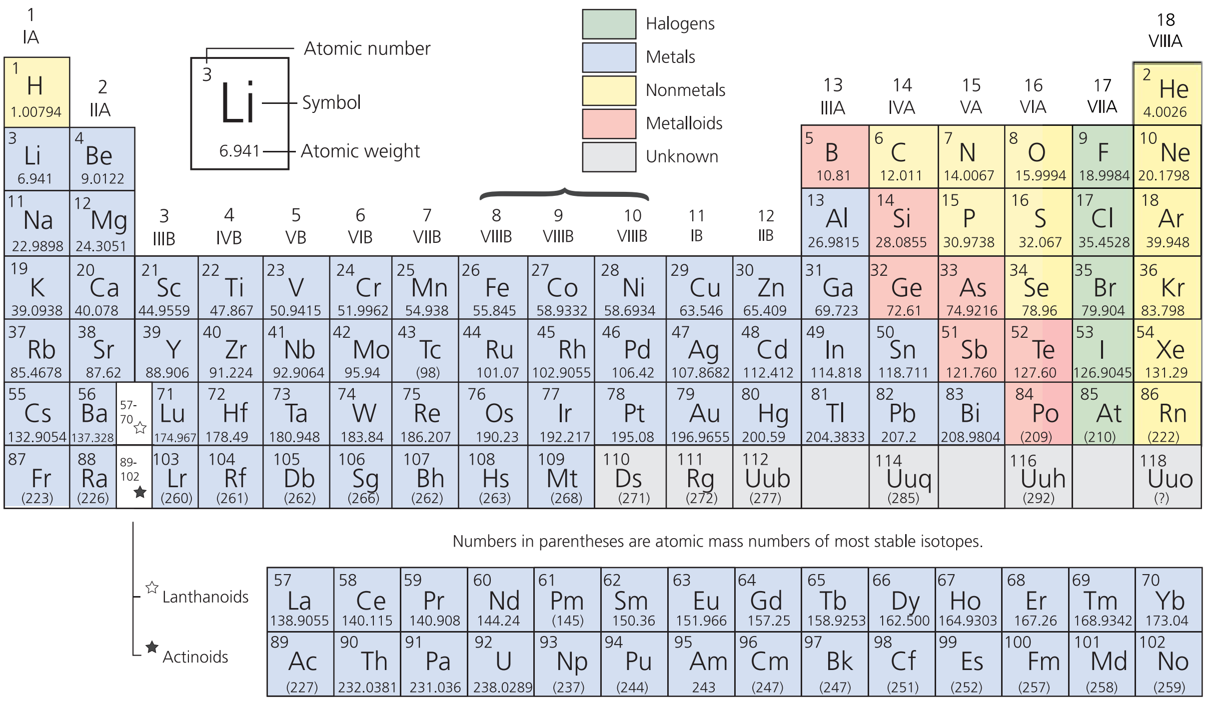
APPENDIX IV
THE GEOLOGIC TIMESCALE

THE GEOLOGIC TIMESCALE

Era	Period	Epoch	Age (millions of years)	First Life-forms	Geology
Cenozoic	Quaternary	Holocene	0.01		
		Pleistocene	3	Humans	Ice age
	Tertiary	Pliocene	11	Mastodons	Cascades
		Neogene			
		Miocene	26	Saber-toothed tigers	Alps
		Oligocene	37		
		Paleogene			
		Ecocene	54	Whales	
		Paleocene	65	Horses, Alligators	Rockies
Mesozoic	Cretaceous		135		
	Jurassic		210	Birds, Mammals, Dinosaurs	Sierra Nevada, Atlantic
	Triassic		250		
Paleozoic	Permian		280	Reptiles	Appalachians
	Carboniferous	Pennsylvanian	310	Trees	Ice age
		Mississippian	345	Amphibians, Insects	Pangaea
	Devonian		400	Sharks	
	Silurian		435	Land plants	Laurasia
	Ordovician		500	Fish	
	Cambrian		544	Sea plants, Shelled animals	Gondwana
Proterozoic			700	Invertebrates	
			2500	Metazoans	
			3500	Earliest life	
Archean			4000		Oldest rocks
			4600		Meteorites

APPENDIX V

PERIODIC TABLE OF THE ELEMENTS



3 Li 6.941 — Atomic number, Symbol, Atomic weight

🟩 Halogens
🟦 Metals
🟨 Nonmetals
🟥 Metalloids
⬜ Unknown

1 IA	2 IIA		3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H 1.00794																		2 He 4.0026
3 Li 6.941	4 Be 9.0122												5 B 10.81	6 C 12.011	7 N 14.0067	8 O 15.9994	9 F 18.9984	10 Ne 20.1798
11 Na 22.9898	12 Mg 24.3051												13 Al 26.9815	14 Si 28.0855	15 P 30.9738	16 S 32.067	17 Cl 35.4528	18 Ar 39.948
19 K 39.0938	20 Ca 40.078		21 Sc 44.9559	22 Ti 47.867	23 V 50.9415	24 Cr 51.9962	25 Mn 54.938	26 Fe 55.845	27 Co 58.9332	28 Ni 58.6934	29 Cu 63.546	30 Zn 65.409	31 Ga 69.723	32 Ge 72.61	33 As 74.9216	34 Se 78.96	35 Br 79.904	36 Kr 83.798
37 Rb 85.4678	38 Sr 87.62		39 Y 88.906	40 Zr 91.224	41 Nb 92.9064	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.9055	46 Pd 106.42	47 Ag 107.8682	48 Cd 112.412	49 In 114.818	50 Sn 118.711	51 Sb 121.760	52 Te 127.60	53 I 126.9045	54 Xe 131.29
55 Cs 132.9054	56 Ba 137.328	57- 70 ☆	71 Lu 174.967	72 Hf 178.49	73 Ta 180.948	74 W 183.84	75 Re 186.207	76 Os 190.23	77 Ir 192.217	78 Pt 195.08	79 Au 196.9655	80 Hg 200.59	81 Tl 204.3833	82 Pb 207.2	83 Bi 208.9804	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	89- 102 ★	103 Lr (260)	104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (262)	108 Hs (263)	109 Mt (268)	110 Ds (271)	111 Rg (272)	112 Uub (277)		114 Uuq (285)		116 Uuh (292)		118 Uuo (?)

Numbers in parentheses are atomic mass numbers of most stable isotopes.

☆ Lanthanoids	57 La 138.9055	58 Ce 140.115	59 Pr 140.908	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.966	64 Gd 157.25	65 Tb 158.9253	66 Dy 162.500	67 Ho 164.9303	68 Er 167.26	69 Tm 168.9342	70 Yb 173.04
★ Actinoids	89 Ac (227)	90 Th 232.0381	91 Pa 231.036	92 U 238.0289	93 Np (237)	94 Pu (244)	95 Am 243	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)

(g) none
(c) nonmetallics

element	symbol	a.n.
carbon	C	6
hydrogen	H	1

(g) chalcogen
(c) nonmetallics

element	symbol	a.n.
oxygen	O	8
polonium	Po	84
selenium	Se	34
sulfur	S	16
tellurium	Te	52
ununhexium	Uuh	116

(g) alkali metal
(c) metallics

element	symbol	a.n.
cesium	Cs	55
francium	Fr	87
lithium	Li	3
potassium	K	19
rubidium	Rb	37
sodium	Na	11

(g) alkaline earth metal
(c) metallics

element	symbol	a.n.
barium	Ba	56
beryllium	Be	4
calcium	Ca	20
magnesium	Mg	12
radium	Ra	88
strontium	Sr	38

(g) none (c) metallics

element	symbol	a.n.
aluminum	Al	13
bohrium	Bh	107
cadmium	Cd	48
chromium	Cr	24
cobalt	Co	27
copper	Cu***	29
darmstadium	Ds	110
dubnium	Db	105
gallium	Ga	31
gold	Au***	79
hafnium	Hf	72
hassium	Hs	108
indium	In	49
iridium	Ir ****	77
iron	Fe	26
lawrencium	Lr	103
lead	Pb	82
lutetium	Lu	71
manganese	Mn	25
meitnerium	Mt	109
mercury	Hg	80
molybdenum	Mo	42
nickel	Ni	28
niobium	Nb	41
osmium	Os****	76
palladium	Pd****	46
platinum	Pt ****	78
rhenium	Re	75
rodium	Rh****	45
roentgenium	Rg	111
ruthenium	Ru****	44
rutherfordium	Rf	104

element	symbol	a.n.
scandium	Sc	21
seaborgium	Sg	106
silver	Ag***	47
tantalum	Ta	73
technetium	Tc	43
thallium	Tl	81
titanium	Ti	22
tin	Sn	50
tungsten	W	74
ununbium	Uub	112
ununtrium	Uut	113
ununquadium	Uuq	114
vanadium	V	23
yttrium	Y	39
zinc	Zn	30
zirconium	Zr	40

(g) pnictogen (c) metallics

element	symbol	a.n.
arsenic	As*	33
antimony	Sb*	51
bismuth	Bi	83
nitrogen	N	7
phosophorus	P**	15
ununpentium	Uup	115

(g) none (c) semimetallics

element	symbol	a.n.
boron	B	5
germanium	Ge	32
silicon	Si	14

(g) actinoid (c) metallics

element	symbol	a.n.
actinium	Ac	89
americium	Am	95
berkelium	Bk	97
californium	Cf	98
curium	Cm	96
einsteinium	Es	99
fermium	Fm	100
mendelevium	Md	101
neptunium	Np	93
nobelium	No	102
plutonium	Pu	94
protactinium	Pa	91
thorium	Th	90
uranium	U	92

(g) halogens (c) nonmetallics

element	symbol	a.n.
astatine	At*	85
bromine	Br	35
chlorine	Cl	17
fluorine	F	9
iodine	I	53
ununseptium	Uus*	117

(g) lanthanoid (c) metallics

element	symbol	a.n.
cerium	Ce	58
dysprosium	Dy	66
erbium	Er	68
europium	Eu	63
gadolinium	Gd	64
holmium	Ho	67
lanthanum	La	57
neodymium	Nd	60
praseodymium	Pr	59
promethium	Pm	61
samarium	Sm	62
terbium	Tb	65
thulium	Tm	69
ytterbium	Yb	70

(g) noble gases (c) nonmetallics

element	symbol	a.n.
argon	Ar	18
helium	He	2
krypton	Kr	36
neon	Ne	10
radon	Rn	86
xenon	Xe	54
ununoctium	Uuo	118

a.n. = atomic number
(g) = group
(c) = classification

* = semimetallics (c)
** = nonmetallics (c)
*** = coinage metal (g)
**** = precious metal (g)

Appendix VI

SI Units and Derived Quantities

DERIVED QUANTITY	UNIT	SYMBOL
frequency	hertz	Hz
force	newton	N
pressure	pascal	Pa
energy	joule	J
power	watt	W
electric charge	coulomb	C
electric potential	volt	V
electric resistance	ohm	Ω
electric conductance	siemens	S
electric capacitance	farad	F
magnetic flux	weber	Wb
magnetic flux density	tesla	T
inductance	henry	H
luminous flux	lumen	lm
illuminance	lux	lx

Appendix VII

Multipliers and Dividers for Use with SI Units

Multiplier	**Prefix**	**Symbol**	**Divider**	**Prefix**	**Symbol**
10^{1}	deca	da	10^{-1}	deci	d
10^{2}	hecto	h	10^{-2}	centi	c
10^{3}	kilo	k	10^{-3}	milli	m
10^{6}	mega	M	10^{-6}	micro	μ
10^{9}	giga	G	10^{-9}	nano	n
10^{12}	tera	T	10^{-12}	pico	p
10^{15}	peta	P	10^{-15}	femto	f
10^{18}	exa	E	10^{-18}	atto	a
10^{21}	zetta	Z	10^{-21}	zepto	z
10^{24}	yotta	Y	10^{-24}	yocto	y

APPENDIX VIII
ASTRONOMICAL DATA

Body	Mass (Kg)	Mean Radius (M)	Orbital Period (Years)	Mean Orbital Radius (M)
Sun	1.991×10^{30}	6.96×10^{8}	—	—
Mercury	3.18×10^{23}	2.43×10^{6}	0.241	5.79×10^{10}
Venus	4.88×10^{24}	6.06×10^{6}	0.615	1.08×10^{11}
Earth	5.98×10^{24}	6.37×10^{6}	1.00	1.50×10^{11}
Mars	6.42×10^{23}	3.37×10^{6}	1.88	2.28×10^{11}
Jupiter	1.90×10^{27}	6.99×10^{7}	11.9	7.78×10^{11}
Saturn	5.68×10^{26}	5.85×10^{7}	29.5	1.43×10^{12}
Uranus	8.68×10^{25}	2.33×10^{7}	84.0	2.87×10^{12}
Neptune	1.03×10^{26}	2.21×10^{7}	165	4.50×10^{12}
Moon	7.36×10^{22}	1.74×10^{6}	27.3 days	3.84×10^{8}

Note: Pluto, which had long been considered a planet, has been recategorized. It now belongs to the class of astronomical bodies called dwarf planets, which are smaller than planets.

Appendix IX

Abbreviations and Symbols for Physical Units

Symbol	Unit	Symbol	Unit	Symbol	Unit
A	ampere	g	gram	min	minute
u	atomic mass unit	H	henry	mol	mole
atm	atmosphere	h	hour	N	Newton
Btu	British thermal unit	hp	horsepower	Pa	pascal
C	coulomb	Hz	hertz	rad	radian
cd	candela	in	inch	rev	revolution
°C	degree Celsius	J	joule	s	second
cal	calorie	K	kelvin	sr	steradian
d	day	kg	kilogram	T	tesla
eV	electron volt	L	liter	V	volt
F	farad	lb	pound	W	watt
°F	degree Fahrenheit	ly	light-year	Wb	weber
ft	foot	m	meter	yr	year
G	gauss	mi	mile	Ω	ohm

APPENDIX X

THE GREEK ALPHABET

Letter	Capital	Small	Letter	Capital	Small
Alpha	Α	α	Nu	Ν	ν
Beta	Β	β	Xi	Ξ	ξ
Gamma	Γ	γ	Omicron	Ο	ο
Delta	Δ	δ	Pi	Π	π
Epsilon	Ε	ε	Rho	ρ	ρ
Zeta	Ζ	ζ	Sigma	Σ	σ, ς
Eta	Η	η	Tau	Τ	τ
Theta	Θ	θ	Upsilon	Υ	υ
Iota	Ι	ι	Phi	Φ	φ, ϕ
Kappa	Κ	κ	Chi	Χ	χ
Lambda	Λ	λ	Psi	Ψ	ψ
Mu	Μ	μ	Omega	Ω	ω

APPENDIX XI

COMMON CONVERSIONS WITHIN THE METRIC SYSTEM

1 meter (m) = 100 centimeters (cm) = 1,000 millimeters (mm)
1 centimeter (cm) = 10 millimeters (mm) = 0.01 meters (m)
1 millimeter (mm) = 1000 micrometers (μm) = 1 micron (μ)

1 liter (L) = 1,000 milliliters (mL)
1 cubic centimeter (cc or cm^3) = 1 milliliter (mL)
1 milliliter (mL) = 1,000 microliters (μL)

1 kilogram (kg) = 1,000 grams (g)
1 gram (g) = 1,000 milligrams (mg)
1 milligram (mg) = 1,000 micrograms (μg)

APPENDIX XII

COMMON CONVERSIONS FROM U.S. CUSTOMARY TO METRIC UNIT VALUES

Quantity	**To Convert From**	**To**	**Multiply by (Rounded to Nearest 1,000th)**
mass	pounds (lb)	kilograms (kg)	0.454
	ounces (oz)	gram (g)	28.350
length	miles (mi)	kilometers (km)	1.609
	yards (yd)	meters (m)	0.914
	feet (ft)	meter (m)	0.305
	inches (in)	centimeters (cm)	2.540
area	square feet (ft^2)	square meter (m^2)	0.093
	square miles (mi^2)	square kilometers (km^2)	2.590
volume	gallon (gal)	liters (L)	3.785
	quarts (qt)	liters (L)	0.946
	fluid ounces (fl oz)	milliliters (mL)	29.574

APPENDIX XIII

TEMPERATURE CONVERSIONS

In the Celsius scale, 0°C is the freezing point of water and 100°C is the boiling point. In the Fahrenheit scale, 32°F is the freezing point of water and 212°F is the boiling point. In the Kelvin scale, 0 K is absolute zero temperature and the freezing point of water is 273.15 K. To convert temperature in degrees Celsius (T_C) to temperature in degrees Fahrenheit (T_F):

$$T_F = \frac{9}{5} T_C + 32$$

To convert temperature in degrees Fahrenheit (T_F) to temperature in degrees Celsius (T_C):

$$T_C = \frac{5}{9} (T_F - 32)$$

To convert temperature in degrees Celsius (T_C) to temperature in kelvins (T):

$$T = T_C + 273.15$$

To convert temperature in kelvins (T) to temperature in degrees Celsius (T_C):

$$T_C = T - 273.15$$

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