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Shimer: An Introduction to Earth History

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AN INTRODUCTION TO EARTH HISTORY

BY

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PREFACE

This volume is an attempt to present a picture of the earth and its life as a consequence of processes which for unmeasured time have operated throughout the universe. It traces on the one hand the sequence of causes and effects which have produced the earth as we know it today, and on the other the succession of living forms which have made the earth their home. In outlining, however briefly, this history of a constantly changing world and its life, and the underlying processes which have shaped the external forms, facts and hypotheses have been drawn from many sources. The author hopes that in every case the distinction has been made clear between the known facts and the hypotheses which investigators have offered to explain them. The volume is planned to serve as a point of view, a general survey to introduce the student to the more detailed knowledge of the earth that can be gained through chemistry, physics, astronomy, geology, and biology.

Among the numerous writers to whom the author is indebted he wishes to mention especially Thomas C. Chamberlin, Joseph Barrell, and Charles Schuchert, as well as the following who have kindly criticized such portions of the manuscript as pertained to their special fields of research: R. A. Daly, P. E. Raymond, H. Shapley, and R. DeC. Ward, of Harvard University; G. R. Wieland of Yale University; H. M. Goodwin, W. F. Jones, W. Lindgren, F. J. Moore, and D. A. MacInnes, of the Massachusetts Institute of Technology.

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AN INTRODUCTION TO EARTH HISTORY

From cause to effect, under the impulse of definite laws, matter and life have evolved from simplicity to complexity. Under the action of these laws continuously working through eons of time, affecting the minute electron as well as the huge nebula, continents and ocean basins as well as their life, evolution has proceeded. Under the action of definite laws this evolution proceeds from cause to effect; from the simple hydrogen atom to the rest of the ninety known atoms, thence to the quarter-million known substances; from the nebula to the various kinds of stars, thence to the planets circling about the stars; from the earth with the sun shining upon it to the development of winds, rain, rivers, and glaciers; from very simple aquatic plants and animals through amphibious groups to highly complex land forms. As Charles Kingsley well says, "We knew of old that God was so great that He could make all things, but behold He is so much greater even than that, that He can make all things make themselves."

I

THE COSMICAL HISTORY OF THE EARTH

In the laboratory of the Master no reaction occurs except according to law. — BAILEY WILLIS

CHAPTER I

MATTER: ITS UNITY AND EVOLUTION

ALL MATTER REDUCED TO NINETY-TWO ELEMENTS

A century and a half of scientific chemistry has shown that all matter as it exists upon earth consists of combinations and rearrangements of the atoms of ninety-two elements. In other words, all of the quarter of a million compounds of matter known to us can be reduced to this limited number of elementary substances, each of whose molecules contains only one kind of atom. Thus, a pound of salt (sodium chloride) is made up of x molecules of salt, while each molecule is composed of one atom of sodium and one atom of chlorine; these atoms are elements. In such substances as native copper, mercury, sulphur, and the diamond only one kind of atom enters into the formation of the molecule.

Molecules are exceedingly small. When the dyestuff fuchsine is dissolved in alcohol, it is observed that a solution of 1/200,000,000 of a gram in one cubic centimeter has a distinct color. The diameter of these molecules varies but is of the order of magnitude of 10^{-8} centimeters.

ALL ELEMENTS PROBABLY REDUCED TO ONE KIND OF ATOM, SHOWING FAMILY RELATIONSHIP

The properties of an atom are related to its weight. Not only, however, do these few elements and their combinations form all known matter, but they are intimately related to one another, bearing within themselves proofs of a common ancestry. The principal evidence of this relationship is found in the periodic law of the elements. Duncan calls this "God's alphabet of the universe," by means of which we may hope to spell out the history of creation. This law states that if we know the weight of the atom of an element, we can then determine the various properties of the element, for these bear a fixed relation to the properties of those elements which are above it and below it in weight. Mendel´eff, who first distinctly formulated this law, predicted the properties of the element germanium before it had been discovered. In his table expressing this law an element with a certain weight was missing, and from its position it was determined that it should possess certain definite qualities regarding boiling-point and melting-point, magnetic characteristics, atomic volume, hardness, etc. When, later, in 1886, this element was discovered by Winkler, its properties were found to have been prophesied with incredible exactness. It is this law of family relationship that has demonstrated the existence of ninety-two elements and has predicted many of the characteristics of the four which have not yet been isolated.

In the table expressing the periodic law (Table I) each element has a particular compartment where it alone can go. This position is determined by the weight of the atom, and when this is fixed, its other properties must of necessity follow from its series and group relations. In each vertical column the elements are closely allied, forming natural groups, the members of which are commonly associated in nature; such groups, for example, are Mg and Ca, Ca and Zn, Fe and Ni. Horizontally a progressive change in atomic weights is shown, which is accompanied by a systematic variation of properties, chemical and physical. The gaps supposedly correspond to unknown elements. The elements scandium, gallium, and germanium were thus described in advance of their actual discovery. The elements most abundant on earth are those of the lower atomic weights, occurring in the uppermost third of the table, as may be seen by comparing with Table II.

Radioactivity. The family relationship of the elements is further demonstrated by the discovery of the Curies and others that the element uranium gradually changes, through the natural giving off of particles which are charged helium atoms, to radium and lead (Table III). This suggests that

TABLE I. CLASSIFICATION OF THE BETTER-KNOWN ELEMENTS ACCORDING TO THE PERIODIC LAW[1]

Type of hydride		RH	RH_2	RH_3	RH_4	RH_3	RH_2	RH			
Type of oxide		R_2O	RO	R_2O_3	RO_2	R_2O_5	RO_3	R_2O_7	RO_4		
SERIES	GROUP 0	GROUP I	GROUP II	GROUP III	GROUP IV	GROUP V	GROUP VI	GROUP VII	GROUP VIII		
1	**2** He = 4.0	**3** Li = 6.94	**4** Gl = 9.02	**5** B = 10.82	**6** C = 12.00	**7** N = 14.008	**8** O = 16.0	**9** F = 19.0			
2	**10** Ne = 20.2	**11** Na = 23.0	**12** Mg = 24.32	**13** Al = 26.96	**14** Si = 28.06	**15** P = 31.024	**16** S = 32.06	**17** Cl = 35.46			
3	**18** A = 39.9	**19** K = 39.095	**20** Ca = 40.07	**21** Sc = 45.1	**22** Ti = 48	**23** V = 50.96	**24** Cr = 52.01	**25** Mn = 54.93	**26** Fe = 55.84	**27** Co = 58.97	**28** Ni = 58.69
4		**29** Cu = 63.57	**30** Zn = 65.37	**31** Ga = 69.72	**32** Ge = 72.6	**33** As = 74.96	**34** Se = 79.2	**35** Br = 79.916			
5	**36** Kr = 82.9	**37** Rb = 85.44	**38** Sr = 87.62	**39** Y = 89	**40** Zr = 91.0	**41** Cb = 93.1	**42** Mo = 96.0	**43**	**44** Ru = 101.7	**45** Rh = 102.9	**46** Pd = 106.7
6		**47** Ag = 107.88	**48** Cd = 112.4	**49** In = 114.8	**50** Sn = 118.7	**51** Sb = 121.77	**52** Te = 127.5	**53** I = 126.932			
7	**54** Xe = 130.2	**55** Cs = 132.81	**56** Ba = 137.37	**57** La = 138.91	**72** Hf = 180 (?)	**73** Ta = 181.5	**74** W = 184.0	**75**	**76** Os = 190.8	**77** Ir = 193.1	**78** Pt = 195.2
8		**79** Au = 197.2	**80** Hg = 200.6	**81** Tl = 204.3	**82** Pb = 207.2	**83** Bi = 209.0	**84** Po = (?)	**85**			
9	**86** Rn = 222.0	**87**	**88** Ra = 225.95	**89** Ac = 230 (?)	**90** Th = 232.15	**91** Ux_2 = (?)	**92** U = 238.17				

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[1] The atomic weights are in light type. The atomic numbers (in heavy type) represent the number of positive charges on the nucleus of the atoms and correspond to the number of electrons arranged outside the nucleus. Hydrogen, with an atomic number of 1 and an atomic weight of 1, is omitted from the table, as are also the rare earth elements of atomic numbers 58–71.

transformation of the elements of higher atomic weight into those of lower weight may be very generally taking place around us today.

The time column in the table represents the time in which half of a given substance will have been transformed into another substance. Thus, eight successive ejections of an alpha particle (helium nucleus with its two positive charges), separated by other minor changes, result in the formation of a lead atom out of an atom of uranium. A similar degradation has been studied in other elements, such as thorium. (The atomic weight of lead derived from thorium is about one unit higher than in normal lead, while lead derived from radium is about one unit lower.)

More lately Rutherford has transformed six elements of higher atomic weight into elements of a lower atomic weight. For example, he has broken down nitrogen under bombardment by alpha particles, moving with a velocity of about 12,000 miles (19,000 km.) a second, into 3 helium and 2 hydrogen atoms. Now the helium atom is known to be made up of 4 hydrogen atoms, thus giving a total of 14 hydrogen atoms for nitrogen, which is the atomic weight of nitrogen.

Such facts have brought physicists and chemists to the tentative conclusion that all elements are hydrogen atoms bound together in various ways and in varying numbers; that is, the atom of each element is a different arrangement of a common stuff.

Relation of temperature to complexity of matter. Usually high temperatures tend to dissociate compounds into their elements and possibly to reduce elements of higher atomic weight to those of a lower atomic weight. The application of heat to ice makes the molecules of the ice move faster, reducing the solid to liquid water. The application of more heat further increases the movement of the molecules until they are forced out as the gas steam. If the heat is increased still more, the molecules of the substance water (H_2O) separate into the elements hydrogen and oxygen. In the same manner sodium chloride, under the application of heat, becomes resolved into sodium and chlorine. (Exceptionally, as with nitrous

Table II. Average Composition of Known Terrestrial Matter as known at the Surface of the Earth[1]

	Lithosphere, 93 per cent	Hydrosphere, 7 per cent	Average including Atmosphere
Oxygen	47.33	85.79	50.02
Silicon	27.74	....	25.80
Aluminum	7.85	....	7.30
Iron	4.50	....	4.18
Calcium	3.47	.05	3.22
Magnesium	2.24	.14	2.08
Sodium	2.46	1.14	2.36
Potassium	2.46	.04	2.28
Hydrogen	.22	10.67	.95
Titanium	.46	....	.43
Carbon	.19	.002	.18
Chlorine	.06	2.07	.20
Bromine	...	.008	...
Phosphorus	.12	....	.11
Sulphur	.12	.09	.11
Barium	.08	....	.08
Manganese	.08	....	.08
Strontium	.02	....	.02
Nitrogen	....	....	.03
Fluorine	.10	....	.10
All other elements	.50	....	.47
	100.00	100.000	100.00

Table III. Reduction of Uranium into Atoms of Lower Atomic Weight

	Atomic Weight	Half Value Period
Uranium	238.5	6 billion years
Uranium X	234.5	1 minute
Ionium	230.5	20,000 years
Radium	226	2000 years
Radium emanation	222	3.85 days
Radium A	218	3 minutes
Radium B	214	26.8 minutes
Polonium	210	136 days
Lead	206	stable

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[1] For an accumulation of many facts concerning the chemistry of the earth see F. W. Clarke, "Data of Geochemistry" (1925), United States Geological Survey, *Bulletin 770.*

oxide (NO), the substance becomes more stable with increase of heat.) Thus, experiments show that high temperatures usually tend to dissociate molecular compounds into their component elements.

As shown by laboratory experiments, the hotter the substance is, the farther its spectrum extends into the violet and ultraviolet region. This fact applied to the stars would mean an increase in temperature from red through yellow to blue, for as we go from red to blue stars the spectrum stretches farther and farther into the ultraviolet region. In other words, red stars have the shortest spectra, almost wholly lacking violet light, and so must have the lowest temperature; yellow stars have spectra elongating toward the violet and are of intermediate temperature; while the spectra of the bluish-white stars extend farthest into the ultraviolet and are thus of the highest temperature.

As we proceed from a dark and superficially cold body, such as the earth, through the red to the white stars, substances decrease in complexity. In the red stars we find the molecular compounds very greatly reduced from those of the earth, though many are still present, such as oxides of titanium, zirconium, and carbon. These become dissociated into their respective elements in the yellow stars, except that they reappear in the cooler sun spots.

Not only, however, do compounds thus become reduced in the hotter stars, but the number of elements appears gradually to become less until, in the blue stars, only helium and hydrogen remain in any abundance. As viewed through the spectroscope, hydrogen, with an atomic weight of 1, and helium, with an atomic weight of 4, are the only prominent elements present in the very hot blue stars and hot nebulæ. Magnesium (atomic weight 24) and calcium (40) are very slightly represented in the blue stars. The metallic elements, such as titanium (48) and iron (55), appear prominently for the first time in the yellow stars and increase to maximum in the red stars; while rubidium (85) etc. appear earliest in red stars, and also at a comparable heat stage in the cooler spots of our sun, which is a yellow star.

It is believed by many physicists and astronomers that the heavier elements do not disappear but are so modified as to be unrecognized in the spectroscope; that, as indicated by laboratory experiments, the heat of even white stars is not sufficient to break down an atom into other elements; and that all the heat of the star does is to knock off some of the electrons of the atoms, so that we cannot recognize them. The nuclei of the heavier elements may be more easily dissociated than are those of the lighter elements, thus causing an apparent decrease in complexity of matter as the temperature of the stars increases.

The building up of matter in the past. According to these latter scientists the development of the heavier elements from lighter ones takes place not in the hot stars but in the still earlier evolution of the nebula, under conditions involving absorption of energy as yet unknown on the earth. That is, somewhere in the nebula, presumably through the heat or electrical energy present, arises the hydrogen atom. Still under the influence of great energy the union of hydrogen atoms gives rise to more and more complex elements. Decrease in heat (shown in the evolution of stars from white through yellow to red and finally into dark bodies) permits the union of the elements producing complex compounds. This last phenomenon is still taking place upon our earth, a dark body, in the cooling of any molten rock and in the formation of metamorphic rocks.

THE ATOM PARTIALLY REDUCED TO ENERGY

When alpha particles (positively charged helium nuclei) are shot out of uranium, they are charged with positive electricity, but before they have traveled far they have become neutral; they have picked up two negative charges of electricity which neutralize the two positive ones, and it is this neutral particle which the spectroscope shows to be the helium atom. The negative electrical charges have received the name of *electrons*. Electrons are likewise given out during the degradation of uranium; they are given off at such tremendous speed that when they strike certain substances they develop phosphorescence, take photographs through solid objects, and heat platinum to redness. The electron is an essential part of all atoms.

The electron is the ultimate unit of negative electricity. The simplest known atom, that of hydrogen, consists of one negatively charged electron and a positively charged nucleus. This hydrogen nucleus is known as the *proton* and is thought by many to be positive electricity. The four hydrogen atoms positively charged, plus the two negative electrons, for example, which go to form the helium atom, must be held together by an intense field of force to give it a unity. From many experiments, as that of Rutherford upon the atom, given above, it is held that the nucleus of each atom is made up of combinations of helium and hydrogen atoms (to form the positively charged nucleus) and electrons (to give it a neutral character) held together by an intense field of force. Thus matter is reduced to positively charged hydrogen nuclei plus electrons. Whether or not this nucleus is simply a positive charge of electricity or a positively charged material nucleus, about which the electrons revolve as planets about their sun, is still unknown. It is believed probable that the spacing and arrangement of the electrons about the nucleus determine the chemical and many of the physical properties of the elements (Harkins).

SUMMARY

Negative electricity, of unknown origin, gives rise to the electron. A nucleus of unknown, possibly likewise electrical, origin, involving one positive charge of electricity, similarly of unknown origin, attracts to itself one electron, becoming the neutral hydrogen atom, the most stable of all atoms. Four hydrogen atoms, through a source of energy probably derived from the stars or nebulæ, unite into the helium atom, and combinations of these result in atoms of still higher atomic weight, giving rise to the ninety-two different kinds of atoms called elements. The union of these elements in various proportions through the forces of chemical affinity, cohesion, and adhesion, possibly connected with the electron, gives rise to all known substances.

The atom is thus an electropositive nucleus attended by few or many electrons. Apparently the nucleus of an element consisting of few protons and electrons can hold these together more firmly than one with many. Substances of high atomic weight in which there are many nuclear electrons and protons which tend to break away are called radioactive.

TABLE IV. SUMMARY OF THE EVOLUTION OF KNOWN SUBSTANCES

Proton = the positive electricity, or the positively charged matter, forming the H nucleus
Electron = negative electricity
1 proton + 1 electron = hydrogen atom
4 H atoms + 2 electrons + energy from the nebula = helium atom
H and He atoms in various combinations + energy from the nebula = atoms of our ninety-two elements
These elements in various combinations give rise to all known substances

TOPICAL REVIEW

All matter reduced to ninety-two elements
All elements probably reduced to one kind of atom, showing family relationship
  The properties of an atom are related to its weight
  Radioactivity
  Relation of temperature to complexity of matter
  The building up of matter in the past
The atom partially reduced to energy
Summary

CHAPTER II

THE PLACE OF THE EARTH IN THE COSMOS

COMPONENTS OF THE COSMOS

Within the vast space surrounding the earth, open to present observation, there is evidence of an orderly though complex material system. Within this cosmos a minor part, though to us the most important one, is the solar system, consisting of a star (our sun) and its attendant planets. This solar system and all the stars visible to the naked eye, and many more, comprise what we know as the stellar system. Many of these stars are mutually dependent. In the Great Cluster in Hercules (Messier 13) are 30,000 visible stars, each brighter than our sun, some a thousand times as bright. These travel through space together, probably revolving about a common axis, for the cluster has a longer and a shorter diameter. Still other groupings of apparently interdependent stars are seen in such star groups as the spiral nebulæ; these are considered by many astronomers to be systems comparable in composition to the stellar system in which we are. Thus the components of the cosmos are our stellar system and the spiral nebulæ.

All bodies in space, individuals as well as groups, except possibly the cold nebulæ and the diffuse bright nebulæ, are in motion. The rotation of the earth upon its axis carries a man at the equator at the speed of over seventeen miles a minute, while the earth is moving around the sun at the rate of eighteen and a half miles a second. At the same time our sun with its attendant planets and comets is rushing through space in the direction of the star Vega at the rate of twelve miles a second. What other motions we may be partaking of within our stellar system, or what is our relation to the billion stars therein, is not yet known. Apparently all these stars are revolving about some center or axis, as the system has a greatly extended equatorial diameter — the Milky Way. It should also bear some relation to the other distant groupings of stars, such as the spiral nebulæ.

COMPONENTS OF OUR SOLAR SYSTEM

Our solar system consists of the sun, about which revolve eight large planets with their twenty-seven moons, a thousand known small planets (asteroids), the zodiacal light material, comets, and meteors. Our sun, an ordinary star, contains $99\frac{6}{7}$ per cent of all the material in our solar system, yet its average density is only slightly greater than that of water. Over forty of the elements found on the earth have been recognized likewise in the sun, either as simple elements or in combinations of more complicated molecules. These elements include hydrogen, helium, carbon, oxygen, sodium, magnesium, silicon, aluminum, potassium, calcium, titanium, iron, copper, zinc, silver, tin, barium, and lead.

Meteorites contain at least twenty-five known terrestrial elements (oxygen, silicon, iron, aluminum, nickel, carbon, etc.), and no elements have been found in them that are not known upon the earth. Comets give evidence of carbon, nitrogen, oxygen, and sodium, and, similarly, of nothing unknown upon the earth.

TABLE V. SOME FACTS ABOUT OUR SOLAR SYSTEM

	TIME OF REVOLUTION ABOUT SUN	NUMBER OF MOONS	MILLIONS OF MILES FROM SUN	SPEED IN ORBIT IN MILES PER SECOND	DIAMETER COMPARED TO EARTH	DENSITY (WATER =1)	GRAVITY (AT SURFACE OF EARTH =1)
Minor planets							
Mercury . . .	88 days		36	30	1/3	4.4 ?	0.2 ?
Venus	225 days		67	22	−1	4.9	0.8
Earth	1 year	1	93	18.5	1	5.5 +	1.0
Mars	1.9 years	2	141.5	15	1/2	3.9	0.4
Planetoids (asteroids) . . .	1.75–8 years		variable	variable	av. 1/3000	3.0 ?	variable
Major planets							
Jupiter . . .	12 years	9	483	8	11	1.3	2.6
Saturn	29.5 years	10 and rings	886	6	9	0.7	1.2
Uranus. . . .	84 years	4	1783	4	4	1.2	0.9
Neptune . . .	165 years	1	2794	3	4	1.1 ?	0.9
Sun.					108	1.41	27.6

The speed in the orbit increases from the outermost planet, Neptune, to the innermost, Mercury, while the time of revolution about the sun decreases in the same direction. All planets revolve about the sun in the same direction and nearly in the same plane. Asteroids vary in size from a diameter of 485 miles down to an unknown size, for the limit of present telescopic power is a diameter of about five miles.

Our solar system is so huge that it takes light, traveling at a rate of 186,000 miles a second, four and a half hours to go from the sun to Neptune; yet in its position in our stellar system it is comparable to a rowboat upon the Pacific Ocean. For it would take light 4.3 years to reach our nearest neighbor, Alpha Centauri; that is, this sun is distant from us 4.3 light years. The next nearest sun is distant 6.5 light years, and the Dog Star, Sirius, is 9 light years away. That means, for example, that we upon the earth would see an event happening upon Sirius 9 years after its occurrence. The average distance between suns is from 6 to 8 light years.

COMPONENTS OF OUR STELLAR SYSTEM

Our stellar system comprises all the stars visible to the naked eye, besides myriads of others. Within it are separate stars or suns, giant and dwarf in size, star clusters (such as the Great Cluster of Hercules with over 30,000 suns), irregular nebulæ (such as the Great Nebula in Orion and the Trifid Nebula), and planetary nebulæ, with centers more condensed than the outside (such as the Ring Nebula in Lyra).

In shape our stellar system is like a thin watch, with a long equatorial diameter and a short polar diameter. Estimates of its size vary. According to many astronomers these diameters are 40,000 light years and 200,000 light years or even greater. Our sun is near the outer edge of the stellar system, and hence, when we look through the long diameter, we see very many stars, the aggregation of which is called the Milky Way.

To help us visualize the size of our stellar system let us take the Great Cluster of Hercules, which according to Shapley is some 36,000 light years distant. The news which we are today receiving from this cluster left there 360 centuries ago, very many ages before our oldest historical civilizations flourished. Rome was at her zenith only 20 centuries ago, and ancient Assyria was just beginning her great development 17 centuries earlier. When the light which we see today left this cluster, the earth was in the throes of the Pleistocene glacial period. Though light travels 186,000 miles a second, communication even through its means is slow within the cosmos.

GROUPS OF STARS BEYOND OUR STELLAR SYSTEM

Beyond our stellar system are a vast number of nebulæ, many of which have a more or less definite spiral structure and are hence called spiral nebulæ. Some astronomers believe that each spiral nebula is a stellar system, or an "Island Universe," as Humboldt called it, similar to our stellar system and similarly made up of irregular nebulæ and suns and planets. This view, according to these scientists, appears to be indicated by such facts as the following: Of the upwards of a million of these systems now known apparently none occur within our stellar system (Curtis). Their distance from us, largely determined by comparison of the brightness of new stars within the spiral nebulæ and within our stellar system, appears to be from one to ten million light years, while the distance of other nebulæ, stars, etc. is reckoned in the terms of thousands of light years. Stars travel through space at a rate of from eight to twenty miles per second, while spiral nebulæ apparently average some five hundred miles a second. More recently a spiral nebula indicated, by the displacements of the spectrum lines, a velocity of 1125 miles a second (Slipher). The spectroscope (see Appendix) also indicates that the rotation of a spiral nebula upon its axis is extremely rapid, as would be anticipated from the great difference between the polar and equatorial diameters. That each spiral nebula is mainly a collection of suns is indicated by their continuous spectrum, like that of a known star cluster, the bright line spectrum of irregular or planetary nebulæ being very rarely seen. Probably the Great Nebula in Andromeda is our nearest neighbor among the spiral nebulæ.

While some astronomers consider spiral nebulæ as separate systems equal in size to our stellar system, many others maintain that, though each is a separate system of some kind, it is by no means comparable in size to our own, nor so distant as some believe. Some observations would seem to indicate that they are within the outer periphery of our own stellar system, and hence could not compare with it in size.

THE HISTORY OF THE COMPONENTS OF OUR STELLAR SYSTEM

Of the various suggested lines of evolution there are two theories which seem most to merit consideration. According to both, a fundamental factor in the evolution of the stars is the loss of radioactive, electrical, or heat energy through radiation into the intense cold of interplanetary space. The older suggestion may be called the irregular-nebula hypothesis; the newer, the giant-dwarf hypothesis.

1. **The irregular-nebula hypothesis.** According to many astronomers the glowing irregular nebula, in which there is no apparent system or order, is the primitive matter from which have developed and are now developing suns and planets, moons and meteors. An anterior stage is the dark irregular nebula from whose contraction has resulted the glowing irregular nebula. There is apparently very much the same kind of dark, tenuous material within our stellar system, especially within the Milky Way. Such dark nebulæ are indicated by the appearance of those novæ which are apparently due to the rush of a dark star through a dark nebula; the star, because of the resulting friction, rapidly develops intense though superficial heat and brightness, but after its passage through the nebula the brightness disappears almost as rapidly as it arose. If the glowing irregular nebula is small, it may, under the influence of gravity, contract, be set rotating from infall of matter or from the near passage of some star, become spherical, and finally give rise to a single sun. (Planetary or ring nebulæ have apparently too great a velocity to belong to this line of evolution.) If the irregular nebula is very large, it may, con-

densing from several centers, evolve into a group of suns, like the constellation of Orion. Evolution according to this hypothesis is indicated in Fig. 1.

Stars have been divided into six great groups arbitrarily designated by the letters B, A, etc. Class B contains the hottest stars, and so on through A, F, G, K to class M, the coolest stars. That this is the order of evolution of the stars appears to be indicated by many of their characteristics. Helium, for example, decreases in spectrum prominence from class B to class A stars, after which it is absent. Hydrogen, prominent in class B stars, as in Alcyone of the Pleiades, reaches its maximum in A stars, such as Sirius, after which it decreases to M stars. Magnesium reaches its maximum in class A stars and disappears in those of F and G. Titanium, iron, and other metallic elements begin later in A stars or in F and increase to maximum in red stars. Calcium, weak or wanting in B, increases toward the red stars. The spectrum sequence shows a decreasing richness in blue, violet, and ultraviolet light from B (blue) stars down to red stars. The velocity of a star within our stellar system increases from the blue to the red stars. Almost all planetary and irregular nebulæ and class B stars occur in and near the Milky Way, the red stars in all regions. Hydrogen and helium, the simplest of definitely known ele-

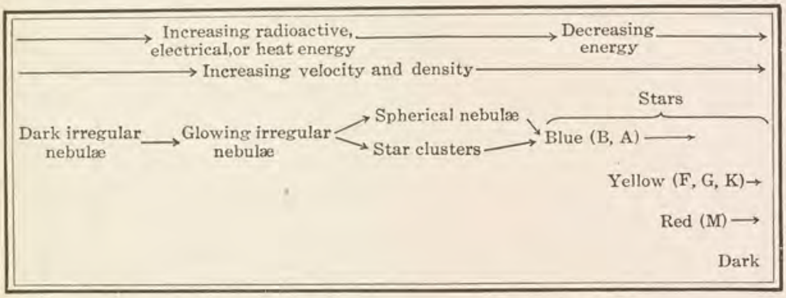

Fig. 1. The evolution of our stellar system according to the irregular-nebula hypothesis

Evolution proceeds from the dark, irregular nebulæ through increase in internal energy, density, and velocity, to the blue stars. Thence, with decreasing internal energy, it proceeds through the yellow and red to the dark stars ments, are most conspicuous in the youngest stars, while the more complex elements make their appearance in the spectra of later, cooler stars. The oxides of titanium and of carbon, for example, found in the comparatively cool red stars, would be dissociated into simpler elements if conditions were changed back into those of class B stars (Campbell).

2. **The giant-dwarf hypothesis.** Most astronomers hold that the theory discussed above gives only half the sequence, and that a distinction should be made between those stars which are so tenuous that they behave as a perfect gas and those which are too dense to behave thus. The accompanying diagram (Fig. 2) illustrates one phase of this view.

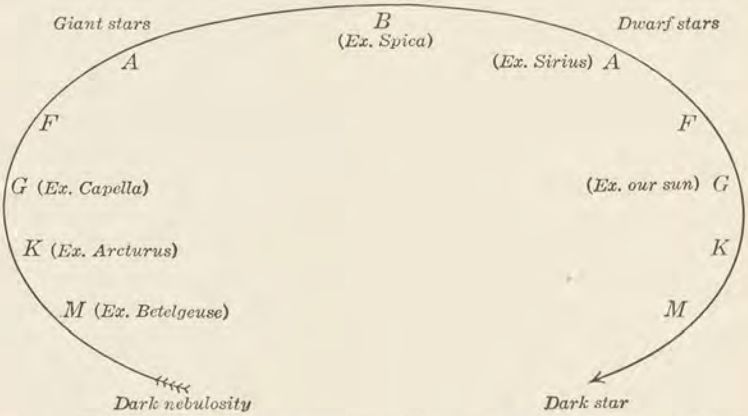

Fig. 2. The evolution of the stars according to the giant-dwarf hypothesis

According to this hypothesis, stars may be divided into two great classes: giant stars, in which the matter is very diffuse, behaving as a perfect gas, and dwarf stars, in which the matter is too dense to behave as a perfect gas.

Evolution is conceived as beginning in a very diffuse dark irregular nebula of unknown origin. It has been suggested, upon the postulate that atoms are made up entirely of energy, that most of the energy set free by the various heavenly bodies is not intercepted by any body but unites into atoms (MacMillan). These atoms could form the basis of dark nebulæ. This hypothesis would, however, only place the beginning of our system farther back but still in some dark nebula. Through the contraction of such a nebula, energy is developed and finally the temperature is raised, and thus the nebula begins to glow, appearing as a very diffuse giant star. The luminescence of very diffuse stars is probably not due to heat but more likely to radioactive or electrical phenomena. Stellar evolution then proceeds to class M stars, which are the most diffuse of all stars, with temperature comparatively low and hence of a red color, as Antares and Betelgeuse. As the gaseous matter in the giant M stars contracts, its temperature, according to Lane's law, must rise and continue rising until it contracts to a point where it becomes too dense to behave any longer as a perfect gas, after which, now a dwarf, it cools and continues contracting. If the mass of a star is very great, it will pass through all the stages to class B, after which it will descend with increasing density through classes B, A, F, G (of which our sun is an example), K, and M to become a dark star. If the gaseous mass is less, it can develop only to class A or F and then descend, and finally, for masses of less than one tenth of the mass of our sun, the temperature would not rise sufficiently high to make the body perceptible to the photographic plate. Thus, Jupiter and Saturn are good examples of such small masses if they have developed directly from a gaseous mass, as they are dark, shining only by reflected light, though of a density comparable to many self-luminous dwarf stars.

In mean density the giant stars should vary from one tenth of that of our sun for class A stars to one twenty-thousandth of the density of the sun for class M stars. That such low densities do occur is shown by that of W Crucis, which is one millionth of that of our sun (Russell). Substantially all naked-eye stars are giants and hence radiate much more light than the dwarfs. Antares, for example, a giant of class M, sends out two thousand times as much light as our sun. Hence, likewise, the vast majority of stars are red and the least abundant are the bluish white ones of class B. A giant of class M is one thousand times as bright as a dwarf of class M; a giant of class K is a hundred times as bright as a dwarf of class K.

3. **Summary.** Our stellar system thus begins its history in an unknown cause, — the original nebulous matter. The loss of energy from numerous condensing centers (bright nebulæ) in the nebulous material changes it gradually into the various known types of stars, probably first into the giant red, yellow, and blue (bluish-white) stars and then into the dwarf yellow, red, and dark ones. The energy given off by the various stellar bodies which fail to encounter any other bodies in space probably gives rise to new dark nebulous matter.

TOPICAL REVIEW

- Components of the cosmos
- Components of our solar system
- Components of our stellar system
- Groups of stars beyond our stellar system
- The history of the components of our stellar system
  - The irregular-nebula hypothesis
  - The giant-dwarf hypothesis
  - Summary
- The spectroscope and its uses (Appendix)

CHAPTER III

THE BEGINNINGS OF THE EARTH

HYPOTHESES OF EARTH ORIGIN

The hypotheses by which science today accounts for the evolution of suns have been summarized in preceding pages; to explain the development of planets revolving about the suns, and of moons accompanying the planets, some additional factors in their origin must be considered.

Apparently, under the laws so far known, no direct condensation of the gas of a nebula, or of a star, into planets could occur, for the dispersive effects of the molecular velocities of the gas, as well as the necessarily very slight gravitative power of a planetary nucleus at the beginning and the centrifugal tendency due to its very slow orbital movement, would be too slight to overcome the much stronger gravitative pull of the central condensing body, the future sun. These considerations, among several others, show such theories as the nebular hypothesis of Laplace (see Appendix) to be inadequate. As yet no hypothesis fully satisfactory to both astronomers and geologists has been suggested. The explanations most favored at present are various phases of the tidal-disruption hypothesis.

1. **The planetesimal, or cold-earth, hypothesis of Chamberlin and Moulton.** According to this hypothesis the following sequence of events is supposed to have taken place. After an irregular nebula had evolved under its own gravitative forces into a star like our sun, the near passage of another star would pull it into a spiral form. The internal forces of our sun are even now hurling matter almost 300,000 miles out into space, with at times a velocity of over 300 miles per second. A near approach of another such star would ease the gravitative pressure of the sun along the line between the centers of sun and star, and would cause greatly increased explosions upon

opposite sides of the sun along this line, and the hurling of matter to heights beyond the sun's ability to pull it back. This escaped matter, which in the case of our solar system was only one seven-hundred-and-forty-sixth (1/746) of the original mass of our sun, would quickly liquefy or solidify in the intense cold and would thus be transformed into bodies revolving around the sun. As a similar succession of phenomena must likewise have been initiated in the passing star, there would result two spiral nebulæ. (The solar nebula that gives rise to a sun with its planets must not be confounded with the huge spiral nebula, the "island universe," which is composed of many stars and nebulæ.) Since the explosions occurring in these spiral nebulæ must have been pulsatory, because of viscous resistances, the matter ejected would be in the form of larger and smaller knots, with much scattered fine material between. The particles of this matter, dustlike in size, would be drawn by the passing star into orbits of considerable eccentricity; and since they revolve about the sun like planets, they have received the name of *planetesimals*.

The knots gradually solidified under gravitation and gathered in the minute scattered planetesimals as their orbits crossed. Thus slowly clearing up their fields of gravitation, so slowly that, according to the original hypothesis, the surface never became sufficiently heated to be molten, eight large knots, irregular in size and at very unequal distances from the sun, grew into the eight planets, while the smaller knots associated with these became the moons. In the zone of the asteroids there was apparently no single dominant knot, and hence each small knot gathered what it could; these smaller knots are the thousand known asteroids of today.

If, at the time of the origin of our planetary system, the greater eruptions of the sun occurred, as they do today, near its equatorial diameter, the influence of the passing star would give to our planetary system its appearance of a closely appressed disk, and cause, as it passed over the equatorial zone, the withdrawal of the maximum amount of material to the greatest distance to form the four large outer planets. Hence the planes of the planetary orbits on this hypothesis would agree in general with one another but not necessarily with that of the revolution of the sun.

According to the planetesimal hypothesis the sun's slow equatorial velocity of 1.2 miles (2 km.) a second was derived from the difference between the impacts of material upon its inner and its outer sides or from the near passage of some earlier celestial body; that is, it is an inheritance from pre-planetary days. The planetary bodies, on the other hand, the appressed form of their orbits, the high momentum, and the 7° obliquity of the common plane of their orbits to that of the sun are due to the near passage of the later star.

The apparent absence of such small spiral nebulæ from our stellar system is not an objection to the planetesimal hypothesis. It is possible that myriads of small spiral nebulæ, such as could form our solar system, and even nebulæ much larger than this, may exist but remain unnoticed. The great distances of even our nearer celestial neighbors would make their discovery impossible with our present instruments. Similarly, the postulated originally spiral form of the solar nebula may have been of short duration; for after a few revolutions, owing to the different periods of revolution of the planetary nuclei about the sun, the initial form would have disappeared (Barrell).

2. **The planetoidal, or hot-earth, hypothesis according to Barrell.** Accepting the disruption of the sun suggested by Chamberlin and Moulton, Barrell maintains that the primitive earth knot was built up to its present size rapidly, not slowly, as postulated by these authors. The incoming material is thought to have varied in size up to masses hundreds of miles in diameter, a size equivalent to that of the planetoids. The impact of this rapidly accumulating material produced sufficient heat to melt the surface of the growing earth. Finally the path was almost entirely cleared by the earth and the other dominant nucleus, the moon, and growth was complete.

3. **The Jeans and Jeffreys hot-earth hypothesis.** A similar molten earth is attained by these authors, though their mathematical results would give to the largest nuclear masses within the arms developed through the tidal disruption of the sun a gaseous state, to the smaller ones a liquid state, and to very

small masses a solid state. Gradually, from the larger of these nuclei, the solid planets would develop.

A molten earth. Covering the molten surface during its later stages there must have been, according to Barrell, a dense atmosphere of water vapor, carbon dioxide, carbon monoxide, chlorine, and hydrochloric acid. Water vapor, penetrating the fluid rock by solution, as oxygen penetrates water today, would enable the molten rock to remain liquid until it cooled below 800° C., that is, at temperatures where there would be but little dissociation of water vapor into hydrogen and oxygen. (Dry granite fuses at from 1300° to 1500°; with water vapor it fuses below 800° C.) Such a dense atmosphere would prevent a rapid loss of heat and would thus enable the various compounds in the hot solution, as each became insoluble, to crystallize out. The heavy basic metals, such as the iron compounds, forming first, as shown by laboratory experiments, would tend to sink, leaving the more siliceous, with feldspar and quartz, to form the surface rocks, just as in a furnace the light slag rises above the heavier metal. This process would be interrupted as the molten matter, welling up as in huge fissure eruptions, repeatedly broke through the thin crust, and engulfed and melted it. Thus the cooled surface rocks would tend to be siliceous, like granite, and the deeper rocks basic (typically basalts), while beneath this and extending to the center of the earth would be the still heavier metals (Fig. 3). With the cooling of the surface rocks would occur the disappearance of the dense cloud envelope encircling the earth, and this would in turn be followed by the gathering of the consequent liquid water into the lower-lying areas of the earth's surface, forming the embryonic oceans, and the shining of the sun upon the earth's surface, giving rise to winds, evaporation, and rainfall.

That the earth was molten during at least an early stage of its growth is suggested by its very high specific gravity as a whole compared to that of the surface rocks, and by its magnetic qualities. These indicate a former fluid state, in which, under gravity, the heavy metals, especially iron, could sink to the center of the earth. (Possibly a somewhat similar result might be brought about, in the solid earth postulated by

Chamberlin, by tidal stresses.) A molten condition of at least the outer part of the earth after it had attained full growth seems to be further shown by the consideration that light igneous rocks (granite and gneisses) are most common in the oldest formations of the earth (that is, in those of early pre-Cambrian time) and that volcanic eruptions in the deep ocean basins are almost entirely basaltic (that is, are nearer the basaltic zone).

On the other hand, if the earth was not molten during its growth, weathering of incoming planetesimals must have occurred from the time when the earth had gained a diameter of approximately 3000 miles, when its mass would be sufficient to hold air and water. Such an amount of weathering upon the fresh

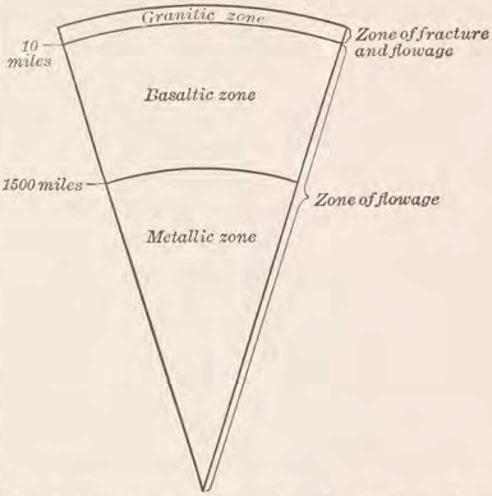

Fig. 3. Diagrammatic section from the surface of the earth to the center, showing postulated granitic, basaltic, and metallic zones

The sedimentary zone, not represented in the section, is discontinuous over the surface of the earth, averaging less than one-half of a mile in thickness, and deepening locally in geosynclines to 8 or 10 miles. The granitic or gneissic zone, 10 ± miles in thickness, is probably likewise discontinuous, not being known in the middle portions of the larger oceans. It forms the larger part of each continent. The basaltic zone is postulated as continuous, rising to the surface in the large ocean basins. From a consideration of the earth's density and the transmission of earthquake waves the basaltic zone is considered to extend, according to Williamson and Adams, to a depth of 1500 miles. Beneath this these authors postulate a metallic zone extending to the center. A metallic zone of this thickness added to the more superficial rocks of low density would give the requisite specific gravity (5.52) of the earth as a whole. The probably necessary transition zones are omitted in the section. The zone of fracture and flowage extends from the surface, where soft muds flow, through increasing depths, at which in succession flow shale, sandstone, limestone, and granite. Beneath this is the zone of flowage. All inequalities in weight are conceived as disappearing at a depth of about 75 miles; hence below this there would be slight opportunity for movement igneous rocks would have made the present oceans a saturated brine. Yet today sea water must be nine-tenths evaporated before NaCl begins to be precipitated. The present amount of NaCl in the ocean and the relatively small amount in the rocks could be derived from a thickness of about 2300 feet of an average igneous rock over the entire earth, that is, about 7000 feet over the present continents (F. W. Clarke). Hence weathering, erosion, and the consequent accumulation of salt could hardly have occurred before the earth became full grown, thus again indicating a molten condition of the earth during its growth.

Summary of earth origin. According to the tidal-disruption hypothesis outlined above, the earth and the other planets of our solar system, together with their moons and the planetoids, are the product of the passage of a star near our ancestral sun. The result of such an approach and passage of a star, with its strong gravitational pull, was the production of accentuated volcanic explosions, or of immense tides, on opposite sides of the sun. Ultimately, it is supposed, the portions of the sun thus drawn away from its center were pulled to a distance so great that they became permanently separated from it. This material naturally issued from the sun in larger and smaller masses or nuclei. The former developed into the planets, the latter into moons and planetoids. The development from a nucleus in one of the armlike offshoots to the present large, solid earth was accomplished, according to one group of thinkers, by the accretion of minute particles to a ball which remained continuously cold. According to another group the earth was liquid when of about its present size. This condition was due either to a growth sufficiently rapid to develop a molten state or to the originally large and liquid state of the nucleus.

TABLE VI

Our ancestral sun (a star) +
near passage of another star =
our solar system with its sun,
planets, moons, etc.

METEORITES

There are still many fragments of matter (meteoroids) revolving around the sun. When these fragments come within the gravitational range of any planet, they are drawn to it. Such a cold meteoroid of interplanetary space, on passing through our atmosphere, has its surface melted and left behind, thus forming the "streak" of shooting stars, the meteors. These are usually consumed by the friction of the atmosphere before they reach the surface of the planet. A meteorite is that portion of a meteor which has reached the surface of the planet unconsumed (Fig. 4). It has been estimated that from 20,000,000 to 30,000,000 meteors strike our atmosphere every twenty-four hours, and that of these only about 1 in 100,000,000 reaches the earth, the rest being consumed through friction with the atmosphere. Of those that reach the earth none exceed a dozen feet in mean diameter. The average size of meteors is

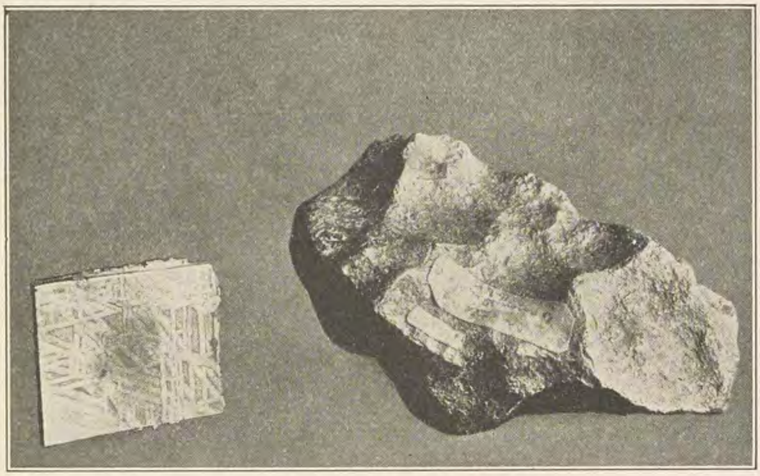

Fig. 4. An iron meteorite from Canyon Diablo, Arizona, showing the pitted character due to surface melting, and a section of one from Texas showing the Widmanstätten figures formed by the coarse crystallization of the nickel-iron

supposed to be that of a grain of wheat. The meteor swarms through which we pass at intervals, especially during August and September, are remnants of comets still revolving around the sun but with material too minute and widely separated to reflect sufficient light from the sun to render them visible to us.

Since meteorites are the only substances that come to us from beyond the confines of our earth, a brief review of their characteristics should throw some additional light upon matter as it exists outside our earth. There are found in meteorites both glassy material, which indicates rapid cooling after melting, and coarse crystals, which could have been formed only under slow cooling. Fragmental material and slickensided surfaces indicate a body subject to varying stresses. There is a noticeable absence of weathering such as takes place at the surface of the earth, showing an absence of water and free oxygen.

These characteristics of composition indicate that meteorites are not due to the gathering together of a few planetesimals, as a raindrop is gathered in the atmosphere, for they must have come from a body sufficiently large to have been melted at the center. Moreover, those meteorites which display coarse crystals and slickensided surfaces obviously cannot have been, in this form, ejections from the gaseous sun. These various conditions which must be fulfilled in any explanation of the formation of the meteorites are apparently found most completely in assuming the disruption of a small, atmosphere-less body like an asteroid (Chamberlin). A body the size of an asteroid is probably held together more by the compression due to gravitation than by cohesion. If, then, the asteroid passes within the Roche limit of a larger body (2.44 times the radius of the larger body), the attraction of this body would cause the disruption of the asteroid into coarse fragments. The passage of some star within even five billion miles of our solar system would very greatly disturb our planets and asteroids, and might even throw them into new orbits in which they might come within the Roche limit of some larger body. Such near passage with consequent disruption would be several times more likely to occur than actual collision. Four comets have been observed to pass within the Roche limit of the sun, and if they had not already been in fragments they would have been disrupted. The fragments of such an asteroid could furnish us with nearly all kinds of meteorites. From deep within the body could come coarsely crystalline fragments; from nearer the surface, the slickensided and fragmental pieces; and from the surface, the glassy material. Similarly, there would be an absence of weathering even at the surface, for so small a body as an asteroid could not hold to itself water and free oxygen. The hydrocarbons present in some meteorites probably have an inorganic origin due to the union of hydrogen and carbon gases; these gases are abundant in meteorites as well as in crystalline rocks upon the earth.

TOPICAL REVIEW

- Hypotheses of earth origin
  - The planetesimal, or cold-earth, hypothesis of Chamberlin and Moulton
  - The planetoidal, or hot-earth, hypothesis according to Barrell
  - The Jeans and Jeffreys hot-earth hypothesis
  - The gaseous hypothesis of LaPlace (Appendix)
  - A molten earth
  - Summary of earth origin
- Meteorites

II

THE GEOLOGICAL HISTORY OF THE EARTH

We have briefly shown how the earth, with its present size and constitution, was very slowly evolved through a continuous series of causes and effects. Some of the steps in this series are still obscure, but enough are known to enable us to form a fairly complete mental motion picture of the whole (see Table IV, Fig. 2, Table VI). From now onward, though some of the causes are extraterrestrial, the effects to be traced are upon the earth itself. We shall consider, first, the sequence of cause and effect as it modifies the earth as a whole; next, the sequence which has produced our present continents and ocean basins; and, lastly, the series which has led up to our present plant and animal life. The first of these includes what is generally known as dynamic and structural geology, while the other two are usually discussed as historical geology and the evolution of plants and animals.

The existence of continents and ocean basins, of mountain systems and river valleys, and their evolution upon the ever-changing face of the earth are due to the interaction of two sets of forces,— the forces which operate at the surface of the earth and those which operate from within the earth. The forces which operate at the surface of the earth originate in the sun and in the pull of gravity and the rotation of the earth upon its axis. These forces, expressed through the agencies of air and water, mold and remold the surface of the earth in an endless cycle of erosion and deposition. The second set of forces originates in the internal heat of the earth itself, aided by the ever-present pull of gravity and the revolution of the earth upon its axis. The internal forces tend constantly to push up high lands and draw down basins, while the external forces make for a reduction of the high lands and the filling up of the low.

FORCES WHICH PRODUCE CHANGES IN THE EARTH

CHAPTER IV

THE INCOMING OF AIR AND WATER, AND THE DEVELOPMENT OF WINDS AND RAIN

SOURCES OF AIR AND WATER

There is evidence that the essentials for the carving and remodeling of the earth's surface were present with the earth in very early times. Hydrogen, carbon, oxygen, and nitrogen are apparently always present upon a cooling star. With increasing cooling the affinity of hydrogen and carbon for oxygen increases, resulting in water and carbon dioxide. Thus, an atmosphere and water would tend to be developed upon such cooling celestial bodies as are large enough to possess sufficient gravitational power to hold them. Such may include bodies as small as even half the present size of the earth. The oceans represent the union of hydrogen and oxygen under such conditions of heat and pressure as make the combination a liquid. The atmosphere consists of those gases which cannot become liquid under the temperature and pressure prevailing at the surface of the earth, and which are yet too heavy to leave the earth's gravitational control.

From the first formation of the earth huge quantities of carbon dioxide, water, and nitrogen have been added from volcanoes. After the earth acquired an atmosphere the passage through it of a mass like a meteorite would heat it and thus set its included gases free. Meteorites have been found to contain, inclosed in minute cavities, large quantities of condensed gas, chiefly hydrogen, carbon dioxide, carbon monoxide, and, in smaller quantities, marsh gas and nitrogen. Since oxygen is not found in the free state in meteorites or crystalline rocks, the oxygen which is so abundant in our atmosphere probably came into existence after the introduction of plants. Plants break up the carbon dioxide, setting free the oxygen and storing the carbon in their tissues. Since much of this carbonaceous matter is later stored in rocks (a storage which we now recognize in the dark color of such rocks), it is probable that the oxygen in the air is largely and continually increased from such sources.

At present the air above the earth consists principally of nitrogen (about 78 per cent), oxygen (about 21 per cent), argon (about 1 per cent), and carbon dioxide (about .03 per cent). Besides these our atmosphere contains a varying amount of transient substances, such as water vapor, which are temporarily thrown off by liquids or solids. The pressure of air at sea level is about 15 pounds per square inch. It decreases in density, and consequently in amount, away from the earth. The atmosphere probably extends outward from the earth's surface for some 620,000 miles, that is, to the point where the attraction of the sun is greater than that of the earth.

THE DEVELOPMENT OF WINDS AND RAIN

A cool globe of sufficient size must, it is seen, hold upon its surface both water and air. The water under gravitation seeks the depressions,— depressions dependent probably upon differential contraction of the earth caused by variation in the density of the material. The surface of such a cool globe would thus become divided into land and water areas, over which would rest the thermal blanket of the atmosphere. The earth is one of the two or three planets of our solar system which are near enough to the sun to receive a considerable amount of heat and yet not so near as to receive too much. Because this solar heat is sufficient to initiate the development of winds and to evaporate water, it must be considered as one of the most prominent of the agents which have modified the surface of the earth and also prepared the earth for the life of future ages.

Given, thus, atmosphere, water, and land upon the planet, with the sun's heat pouring upon it, certain results must follow. Winds are developed, rain falls, and the cycle of erosion and deposition is initiated.

The development of winds. Since the rays of the sun are most nearly vertical in the tropics, it is in equatorial regions that the greatest amount of heat is received. Hence the air in these regions is expanded and rises. If the earth did not revolve upon its axis, the air thus rising at the equator would flow directly north and south to the poles, where, descending, it would return as a surface current to the equator. Because, however, the earth does revolve upon its axis and the meridian zones narrow toward the poles, the layer of air flowing poleward at a high level is deflected more and more to the east (see Fig. 5).

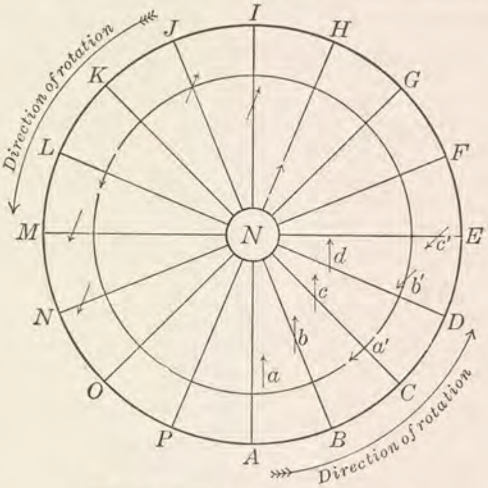

Fig. 5. Origin of surface winds

The Northern Hemisphere rotates eastward in the direction of the marginal arrows. *A*, *B*, etc. are meridians, *N* the north pole. Let arrow at *a* be the direction of a particle of matter (as air) moving toward the pole. When the meridian *A* has in the revolution of the earth advanced to the position of *B*, the particle, which has continued moving in a straight line, will be in the position indicated by the arrow *b*, parallel to *a*; and thus for *c* and *d*. That is, a wind moving toward the north pole is deflected to the right of its course. Similarly a wind (*a′* at *C*) in the Northern Hemisphere blowing toward the west is deflected toward the north (*c′* at *E*), while a wind blowing toward the east becomes deflected toward the south (*L* to *N*); and a wind blowing southward from the pole trends toward the east (*H* to *J*). That is, whatever its direction or height the wind is deflected to the right of its course in the Northern Hemisphere. In the Southern Hemisphere, due to the same cause, it is deflected to the left

The strong eastward-moving winds thus initiated produce a circumpolar whirl, with descending air currents at the poles. These circumpolar whirls, aided by the heat of the equatorial

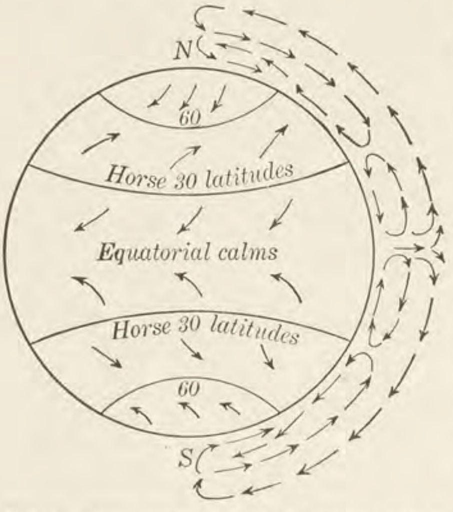

Fig. 6. Ideal circulation of principal winds of the earth (according to Clayton)

The arrows at the side represent a vertical section through the atmosphere and indicate the dominant direction of the surface, intermediate, and upper winds. The arrows upon the face of the earth indicate the direction of prevailing surface winds. The expanded air rising above the warm equatorial regions at first moves toward the west, but it is soon deflected more and more to the right (Northern Hemisphere) and flows poleward aloft, as an intermediate current at or below the level of the highest clouds ("anti-trade"), and then probably most of it descends at about 30° to 35° latitude. The upper current shown in the figure is still somewhat hypothetical, but there is some evidence in favor of its existence (Clayton). Mainly because of the circumpolar whirl above referred to, there is a piling up of air at parallels 30° to 35°, with a consequent flowage from beneath it to the north and south. This piling up is also fed by equatorward-flowing intermediate currents at a height of five to seven miles, as is shown by observations of balloons and especially by the movements of the long, feathery, striated cirrus clouds

regions, cause a piling up of air and hence areas of increased pressure (high pressures) at about 30° or 35° north and south latitude, that is, along the parallel dividing the surface of each hemisphere into equal halves. ("The whole lower air mass may be divided into regions of low and high air pressure, or areas of deficiency or excess, between which lie areas of more nearly normal pressure." — Waldo.)

Because of this heaping up of the air at latitudes 30° or 35° there is a descent of the air, and hence it flows on the surface of the earth both toward the poles and toward the equator. The surface currents moving poleward would be deflected eastward (see Fig. 6), giving the well-known westerlies at the surface of the earth in the temperate zones, while the air moving equatorward would, from the same cause, be deflected to the west, forming the trade winds within the tropics.

Thus the principal terrestrial winds must follow the presence of air upon a rotating globe of sufficient size, heated by a neighboring sun; and, the supply of heat from the sun being continuous, the principal winds must also be continuous. The presence of continents and oceans, of mountains and lowlands, will necessarily bring about certain modifications in these winds. Because of the greater heating of the land during the summer, the cooler and hence heavier air from the ocean tends to blow from ocean to land in the warmer months and vice versa in the colder months. This gives the so-called continental winds, which, when unusually well developed, as in southern Asia, are known as monsoons. A similar but much less marked condition, due to the fact that on hot summer days there is a more effective heating of coastal lands than of the adjacent ocean water, gives rise to the on-shore sea breeze, while during the night, when the land cools more than the water, the land breeze blows off-shore.

An interchange of air between the Northern and Southern hemispheres would also take place, because of the movement of the region of greatest heat north and south, due to the inclination of the earth's axis to the plane of its orbit about the sun.

Friction greatly reduces the rapidity of the winds. The higher winds probably have the highest velocities. The return intermediate equatorial current is much slower, while the surface winds over the land are the slowest. The velocity of winds over land areas at 50 feet elevation is about 25 per cent, and at 100 feet about 50 per cent, of the normal velocities existing over the open ocean.

Development of rain. By the heat of the sun the liquid water present in depressions on the earth's surface is changed into a gas (water vapor). The more the air is heated, the more water vapor it can hold. As the air descends at latitudes from 30° to 35° it becomes warmed by compression, and since in this condition it can hold more water vapor, these regions have dominantly clear weather, and the lands within these latitudes naturally tend to be deserts, although their altitude, their dominant winds, and their relation to other lands or water bodies may modify their aridity. Thus, the great deserts of the earth occur near the parallel of 30°,— Arabia, Sahara, and southwestern North America in the Northern Hemisphere, and western Australia, Kalahari (in South Africa), and northern Chile in the Southern Hemisphere. When air rises, it cools and can consequently hold a smaller amount of water vapor. Hence the invisible water vapor may become visible as clouds. If it cools still more, the vapor particles collect into raindrops and fall upon the earth beneath. For example, the belt of equatorial calms is a region of great rainfall, because the air as a whole is rising and cooling during its ascent. Similarly, when winds pass from an area rich in moisture over a mountain range, abundant rain will fall upon the windward slope. Thus the winds passing westward from the Atlantic over northern Brazil help to convert that country into a jungle, and also give heavy rains on the eastern slope of the Andes. As the air descends, however, upon the leeward side of the mountains (Fig. 7) it becomes warmed by compression and can hence take up more moisture, making the region a dry one, as on the western slope of the Andes in Bolivia. Much rain, however, is due to the forced ascent of the air during storms.

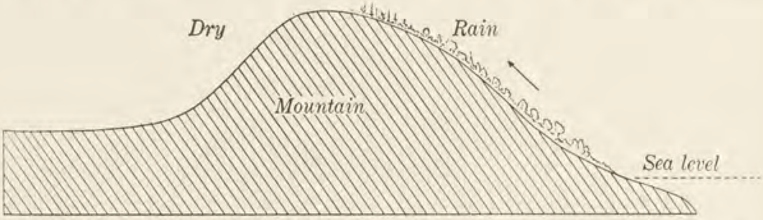

Fig. 7. Diagram to illustrate the origin of moist and dry regions in mountainous districts

The prevailing winds blow in the direction of the arrow; when they reach the higher altitudes in crossing a mountain range, they are cooled so that the air can hold less water vapor, which is consequently condensed and falls as rain, but upon the leeward side of the range, owing to the compression of the air in its descent, they become drying winds

Cyclonic storms. The region of the westerlies is subject to cyclonic storms, usually several hundred miles in diameter, accompanied by shifting winds, considerable areas of cloud, and smaller areas of rain or snow. In these the air at the surface of the earth moves spirally inward to a center of low pressure.

In the Northern Hemisphere it is the western and northern sides of these cyclonic storms that are colder; in the Southern Hemisphere, the southern and eastern sides. Most of the rainfall usually occurs on the side nearest the supply of moisture, and the lower the barometric pressure at the center the stronger the winds and usually the greater the precipitation. The cyclonic whirls usually move in the direction of the primary winds; in North America and Europe this is toward the east and slightly poleward (Figs. 8, 9).

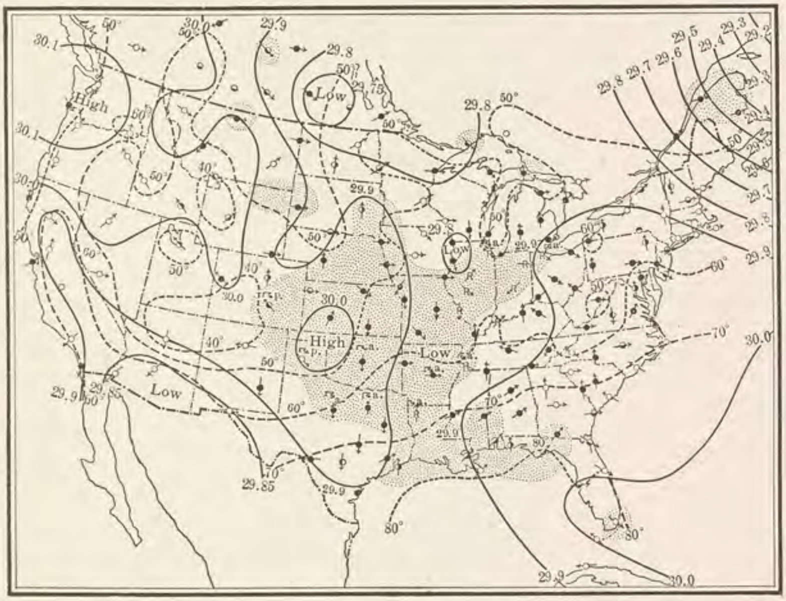

Fig. 8. United States weather map for June 1, 1924, 8 A.M.

Shaded areas show regions of precipitation of .01 inch or more during the last twenty-four hours. Solid lines indicate areas of equal barometric pressure, dotted lines areas of equal temperature. Arrows point in the direction the wind is blowing. Symbols indicate: ○ clear, ◑ partly cloudy, ● cloudy, R rain, ʀ thunderstorms at the station during the twelve hours preceding 8 A.M. Rain is near the front of the low-pressure area, cloudy weather continues westward into the high-pressure belt

The causes of these great whirls of air are still undetermined, but include the following: At the junction of two currents of air flowing at different rates or in different directions, as between the intermediate and surface currents, there is a tendency to form eddies, or whirls. Also, when local areas of the earth's surface become heated much more than neighboring ones, the air is expanded upward with a consequent outflow aloft, a consequently increased downpressure some distance from the upflow, and an inflow at the bottom. The currents are deflected by the force of the earth's rotation to the right in the Northern Hemisphere and to the left in the Southern, and hence a gyratory motion is given to the whole mass of air. When much moisture is present, the great amount of heat liberated during its precipitation (equal to the amount originally necessary to change it from water to vapor) tends to prolong the existence of the low barometer.

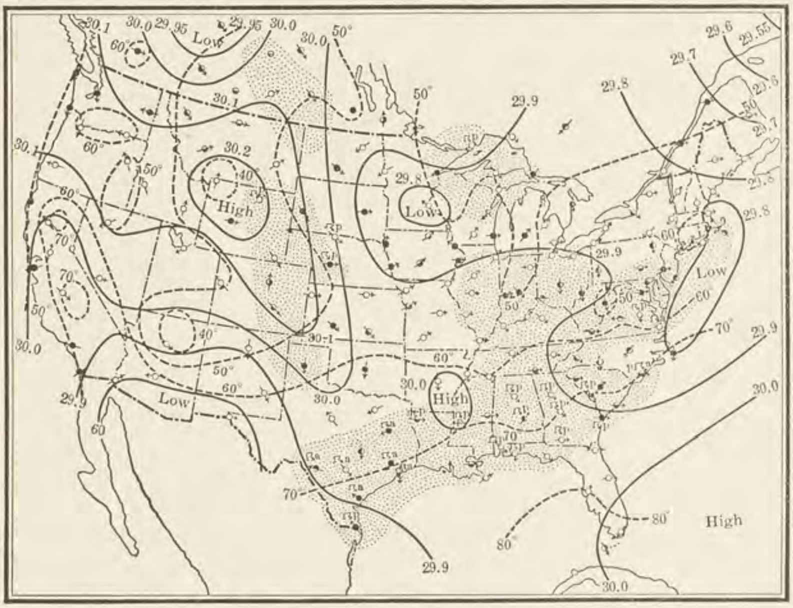

Fig. 9. Weather map for June 2, 1924, 8 A.M.

The cloudy belt has progressed eastward to the coast

TABLE VII. SUMMARY OF ORIGIN OF WINDS AND RAIN

$$\text{Air} + \text{energy of} \left\{ \begin{array}{l} \text{sun's heat} \\ \text{gravitational pull of earth} \\ \text{rotation of earth upon its axis} \end{array} \right\} = \text{winds}$$

$$\text{Water} + \text{air} + \text{energy of} \left\{ \begin{array}{l} \text{sun's heat} \\ \text{gravitational pull of earth} \\ \text{winds} \end{array} \right\} = \text{rain}$$

TOPICAL REVIEW

- Sources of air and water
- The development of winds and rain
  - Cyclonic storms

CHAPTER V

STREAM EROSION

> The hills are shadows, and they flow
> From form to form, and nothing stands;
> They melt like mist, the solid lands,
> Like clouds they shape themselves and go.
>
> TENNYSON

THE WEARING DOWN OF THE LAND

Since the sun shines upon the revolving earth with its blankets of air and water, winds and rain must result; and because the rain falls upon the uneven surface of the land, streams are developed which gradually wear it down and deposit the sediment in lower areas. Since gravity tends constantly to draw the water into the lowest depressions of the earth, the resultant oceans likewise further the wearing away of the land and the deposition of the eroded products. Thus it is that, through the agency of the forces operating at the surface of the earth, that is, the heat of the sun, gravity, and the earth's axial revolution, the land is being continually worn away.

DISINTEGRATION OF THE SOLID ROCKS

Since rocks radiate heat more rapidly than does the air, their temperature at night usually falls so low that the air in contact with them cools below its saturation point. The moisture thus condensed from the air is called dew when it is deposited in the liquid form and hoar frost when deposited in the solid form; it naturally contains a varying amount of free oxygen and carbon dioxide. These gases are likewise present in rain and in other water at or near the surface of the earth. They enter into various chemical combinations with rocks in the processes called oxidation and carbonation, gradually breaking them up into innumerable small particles. Oxygen is especially noteworthy for its tendency to unite with the iron minerals, causing them to crumble away in red or yellow particles, while carbon dioxide unites with the lime of the various minerals, forming lime carbonates. Water sometimes unites directly with minerals in a process called hydration, bringing about the formation of new minerals with a consequent increase of volume. It has been estimated that a granite rock converted into soil is increased 88 per cent in volume, largely as the result of hydration. This process likewise tends to disrupt the rock. Thus, the complex minerals become reduced to simpler compounds, with the consequent decay of the rock. High temperatures usually increase the rapidity of chemical reactions. Rapid changes of temperature tend to break up a rock, while the entrance of water into the cracks thus formed and the subsequent freezing tend further to disrupt it, giving to water still freer access to the rock, where it brings about additional chemical effects. In this manner the solid rocks at or near the surface of the earth become gradually broken up into finer and finer particles, with the resultant production of soil.

DEVELOPMENT OF STREAMS AND THEIR VALLEYS

The impact of raindrops upon the soil loosens the surface particles, which are then carried downward by the flow of these drops. The water running from the broader slopes collects in a stream at their base. Here the greater volume of this small stream gradually cuts through the soil into the solid rock, making this low ground still lower. Thus a *gully* is formed (Fig. 19). Through the continuation of this process the gully develops into a *ravine*, and the ravine expands gradually into a *valley* (Fig. 13). The active agent producing these results is in each case running water,— in the gully, the *rivulet*; in the ravine, the *brook*; in the valley, the *river*.

After the stream is once located by the original slope of the land the gullies entering it continue to increase in length headward, eating into the ungullied areas. This headward direction of the gully is determined by the greatest volume of water which enters it and by the comparative softness of the soil. Thus, as gullies increase in length by headward erosion and in depth and breadth by vertical erosion and through the development of new gullies from their sides, the rivulets in them become brooks, while brooks in the same way grow into rivers.

The total annual rainfall upon the lands of the earth has been estimated by Sir John Murray as over 29,000 cubic miles. Of this, 6500 cubic miles drain off through the rivers to the sea. Since the average height of the land is 2400 feet and since a cubic mile of water weighs over four billion tons, the erosion effect is tremendous, for the same amount of energy is expended as though the water fell vertically.

The tools with which a stream works are the sediment (the mud, sand, etc.), which acts by abrasion, and the active chemical substances, which dissolve the material upon which they work (p. 42). When a stream rolls sand or gravel over its bed, both bed and sediment are worn away to some extent, and this results in a minute deepening of the former and an increasing fineness of the latter. It is the corners of a bowlder in a stream that get worn first, since these are hit most frequently against the stream bed or against other sediment carried along by the water. It is the very frequent repetition of the blows that produces such vast results. Near the source of a large river huge bowlders strew the stream bed; at its mouth are only mud and sand.

If the material over which the stream runs is massive rock, it is most resistant; if it is composed of thin layers or is full of joints, it will, other factors being equal, be eroded more rapidly; while if it is unconsolidated, it will be still more rapidly worn away.

Rapidity of stream erosion. The speed with which a stream will wear down its bed or channel depends upon (1) the amount of rainfall upon that area, (2) the slope of the valley, (3) the tools the stream has to work with, and (4) the character of the rock over which it runs.

The greater the rainfall, other factors being equal, the more rapid the erosion, the more mud will be carried in suspension, and the more material will be dissolved and carried away in solution. Thus, after a heavy rainfall, streams become muddy. Increase in rainfall produces the same results as increasing the slope of the stream beds; both hasten the flow of the water and hence the erosion of the valley. The erosive power varies as the square of the velocity. If, for example, the velocity is doubled, a bridge abutment will be hit in the same time by twice as many sand grains carried along by the water, and each grain will strike with twice its former strength. The velocity depends in addition upon the shape of the channel; if this is crooked, there will be more friction between the water and the sides of the valley than when it is straight, and this friction must slow up the stream.

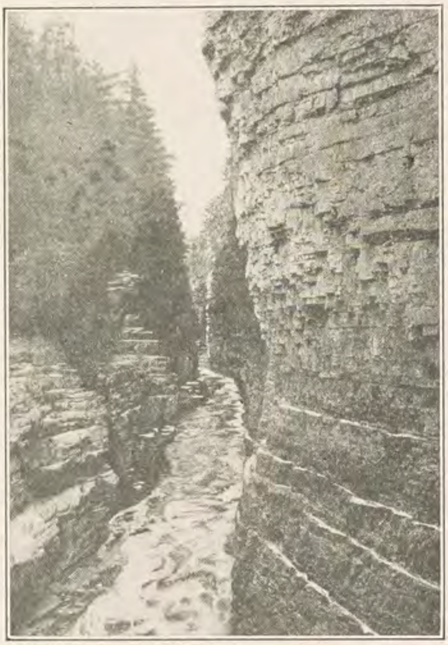

Fig. 10. Ausable Chasm, New York

Note the horizontal strata and the numerous vertical joints cutting them

Features due to stream erosion. Thus erosion produces gullies, ravines, and valleys. When the stream cuts down very rapidly through a hard rock, so that its banks remain steep, a *canyon* is formed, such as Niagara Gorge, or Ausable Chasm (Fig. 10). An arid climate is more favorable to the development of a canyon than is a moist climate. The Grand Canyon of the Colorado would have become a much wider valley in a region of heavier rainfall; for in a moist region much more water would have entered from the sides of the canyon, with resultant gentler slopes. Under the arid conditions present in that region, however, most of the water is derived from the rain

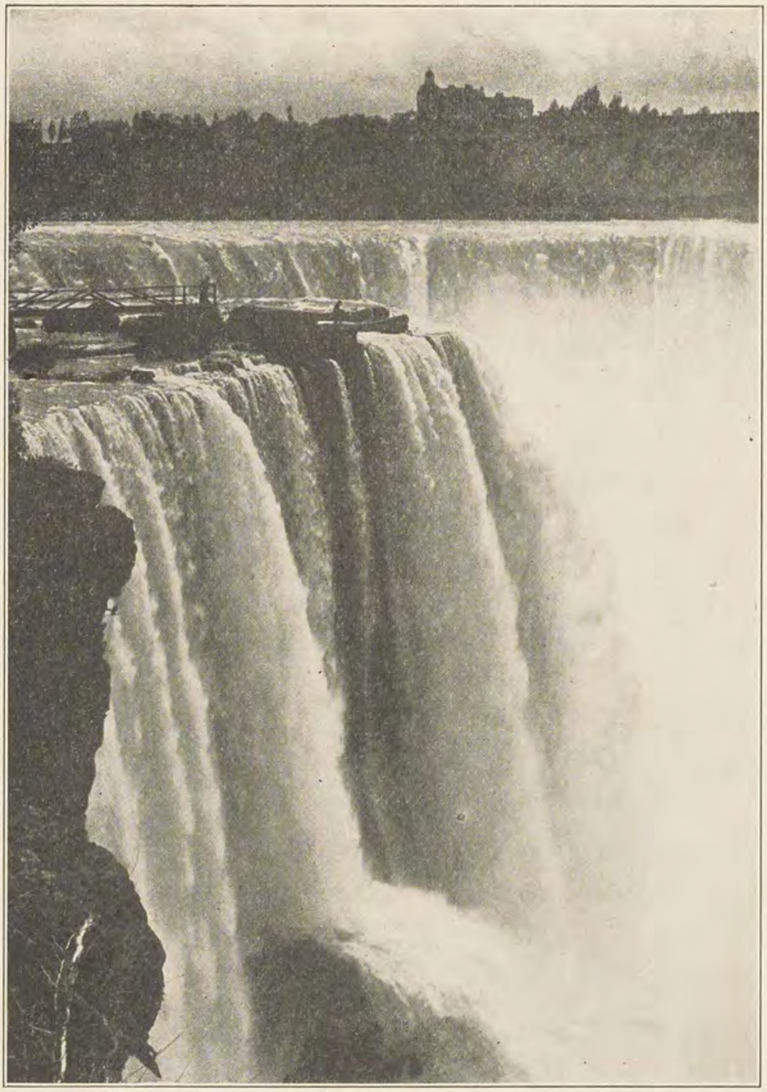

Fig. 11. View of Niagara Falls (Horseshoe Falls)

The resistant rock (Niagara limestone) forming the top of the falls is seen at edge of Goat Island in left foreground. (Courtesy of the United States Geological Survey) that falls in a distant region, the highlands of Utah; and since the work of water owes its power to gravity, its dominant result in this case is downcutting and not widening.

When a stream cuts down through a harder rock overlying a softer rock, *falls* result (Fig. 11). The softer rock wears back faster than the harder rock and undercuts it, causing the harder bed to break off in successive blocks and thus maintain a vertical face over which the water falls. *Rapids* are usually due to a succession of small falls occurring close together. Falls or rapids often cause the development of *potholes,* — bowl-shaped depressions in the surface of a rock. The location of these is probably due in the first instance to accidental circumstances or to local weakness; and subsequently they become enlarged and rounded by the whirling action of the stones carried by the eddying water.

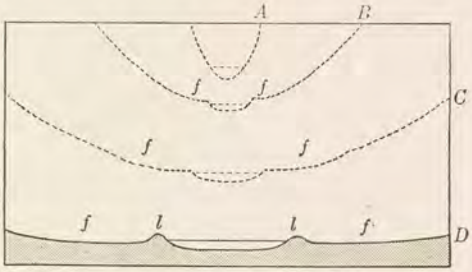

Fig. 12. Idealized cross section of a valley during its growth from youth to old age

As the river continues its downcutting the land is worn away from *A* to *D*, the old-age level, or peneplain. *A*, *B*, early and late youth; *C*, maturity; *D*, old age; *f*, flood plain; *l*, natural levees

Since the rivulets and brooks must all flow downward to enter the river, the area which they drain takes on the shape of a half basin, and thus the entire region is called the *river basin.* The dividing ridge, or watershed, between two basins is the *divide.*

An erosion cycle. Given a sufficient time, unless elevation of the region occurs, a river and its tributaries will wear its entire basin down to approximately the level of its mouth; that is, the basin will pass from its primitive elevated state through a condition of hills and valleys to a final low, level plain. This topographic cycle has been considered as a history divisible into three periods,— youth, maturity, and old age,— a division based not on years but on work accomplished or to be done (Fig. 12). In most cases the interval from maturity to old age probably occupies 100,000 times that from youth to maturity, because erosion must be slower at the lower levels.

Youth is characterized by streams with most of their work before them. The valleys of young streams are thus V-shaped, since there has not yet been time to widen them. Falls and rapids are present, since there has not been sufficient time to lower them to a gentle gradient. Lakes and swamps occur, since the stream has not yet drained them through the combination of cutting down its outlet and filling in its basin. The divides are wide and poorly drained, since the river has as yet acquired but few tributaries. Thus, not only may the Colorado River in Utah and Arizona be called a young stream, but the entire area drained by it is spoken of as a young region.

Maturity is the period during which the streams are doing their greatest work, both in erosion and in transportation. The valleys have been widened so that the streams meander in curves appropriate to their volume. There is almost complete absence of falls and rapids, lakes and swamps. The divides are very narrow, for the rivers have numerous tributaries, and hence the land is thoroughly dissected, and its inhabitants are accordingly isolated. Land capable of being used for agriculture is at a minimum. The southern Appalachian Mountains, in West Virginia, eastern Kentucky, and Tennessee, are an example of such a mature region, as are also the Highlands of Scotland and the Mohawk Valley (Fig. 13).

In *old age* the streams have most of their work behind them. The valleys have been broadened to a plain with such a very gentle slope that the rivers easily turn aside from their direct course and curve in meanders over the flat lands. The divides are low, and hence communication is easy. Agricultural land is at a maximum. Most of the waste from the land is carried in solution. The lower reaches of many of the large rivers of the earth are old. The lower Mississippi River is old, as are likewise the neighboring parts of the states of Louisiana, Mississippi, and Arkansas. When a region becomes reduced to a condition of old age, it is called a *peneplain,* "almost a plain," as the Latin derivation indicates. This level condition may be further accentuated by a slight rise of ocean level, at which time the sea adds its leveling power of erosion to that of the rivers (Figs. 12, *D*; 15).

Growing old may be hastened or retarded. The erosion cycle may, however, be hastened by a depression of the land or may be retarded by its elevation. A geologically recent submergence of the lands bordering the North Atlantic from North Carolina and from France northward to the Arctic has drowned the lower reaches of the stream valleys and has thus reduced the amount of erosion to be done by these streams (Fig. 41).

Fig. 13. The Mohawk Valley east of Canajoharie, New York

An example of a mature region

Growing old is likewise hastened, though with results disastrous to man, by the deforestation of mountain slopes.

Upon the reëlevation of any land area, unaccompanied by tilting, the streams will all retain their old positions, but with renewed youth will cut deeply into the beds beneath them. Since these streams existed before land elevation, they are called *antecedent* streams. A recent elevation of British Columbia has caused the Fraser and Kootenay rivers again to spend their energies in deepening instead of widening their valleys, with the result that each has developed a narrow valley within a broader one. The railroads are situated upon the floor of the old valley, a rocky bench above the present deepening gorge. If the region raised is a broad peneplain, as was the Appalachian mountain area at the close of the Cretaceous period of earth history, the rivers meandering over its broad plains will cut downward, gradually forming broad valleys. These *entrenched meanders* and the even skyline formed by the uneroded remnants of the old peneplain are important emblems upon the coat of arms of the region, revealing its past history (Fig. 14).

If the upheaval of the land is accompanied by tilting, most of the streams will be gradually deflected from their original courses. This is shown by the fact that mountain crests are usually the main divides of river systems. If, however, a stream is sufficiently large and the uplift not too rapid, it may continue in its ancient course, cutting through the uplifted land as fast as this is raised athwart its course, like a saw cutting through a log held against it. Examples of such strong antecedent rivers are the Sutlej, which cuts by deep gorges through the southern ranges of the recently uplifted Himalayas, and the middle Rhine, which is impressing its old meanders deeply into the slate mountains which were raised across its course, thus forming the Rhine gorge of today (Fig. 111).

DEPOSITION THROUGH STREAM EROSION

Material, such as mud and sand, picked up when the current is strong, must be deposited when the current slackens in lower reaches of the stream or disappears in a lake or sea; for the force of gravity, ever present, becomes noticeable in drawing down smaller and smaller particles as soon as the counteracting force of the current sufficiently declines.

Causes of deposition. The energy of a stream may decrease under changed conditions. For one thing, the slope down which it runs may suddenly become less steep. At such localities sand and gravel *bars* are common. The bars are long and narrow, elongated downstream by the flowing water. Furthermore, its volume may diminish through evaporation or through sinking into the ground. This is most common where streams flow from wet, usually mountainous regions over dry plains. The Rio Grande in southwestern United States and the Tigris and the Euphrates in eastern Asia Minor take their rise in mountains, while the Nile gets its annual supply of water in the equatorial rain belt of east central Africa. Other conditions

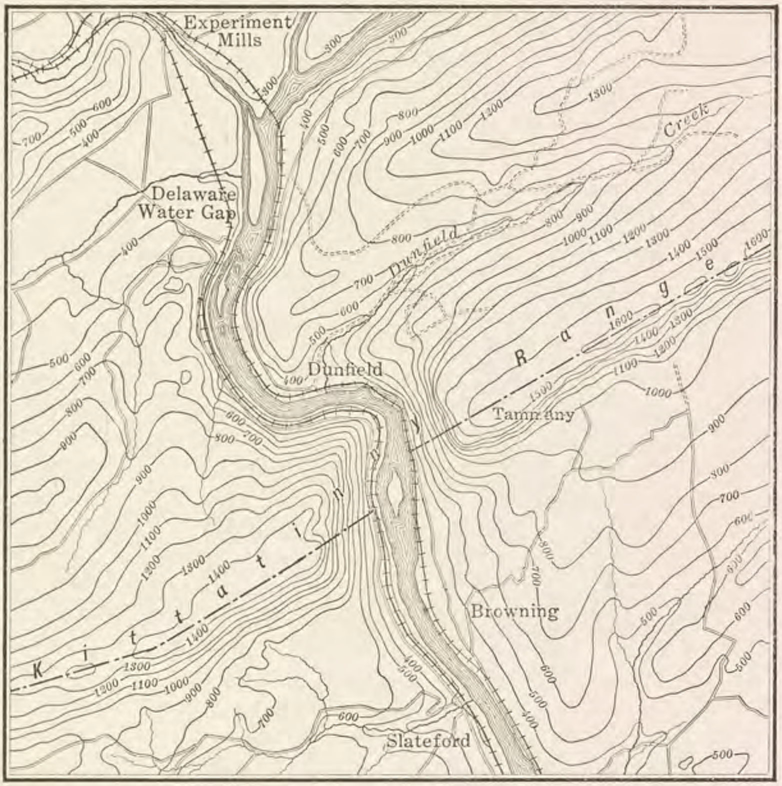

Fig. 14. Delaware Water Gap, Pennsylvania-New Jersey

The Kittatinny Range is a ridge of much harder rocks than the ones to the south and to the north. For this reason it projects as a mountain. The top of this ridge is all that here remains of the old peneplain developed during the Mesozoic. Scale: 1 inch = 1 mile; contour interval = 20 feet) that may affect a stream's energy are changes from a straight to a crooked channel, from a narrow to a broad channel, and from an uninterrupted course to one beset by obstructions such as sunken trees. Usually a decrease in the energy of a stream lies in a combination of the two causes, decrease in slope and diminished volume. This is well seen in the case of the Platte River of Nebraska. Rising in the Rocky Mountains, its branches descend over the Great Plains, carrying great quantities of sediment which, under the influence of evaporation and lessened grade, are deposited in innumerable bars so that the river becomes a braided network of many channels.

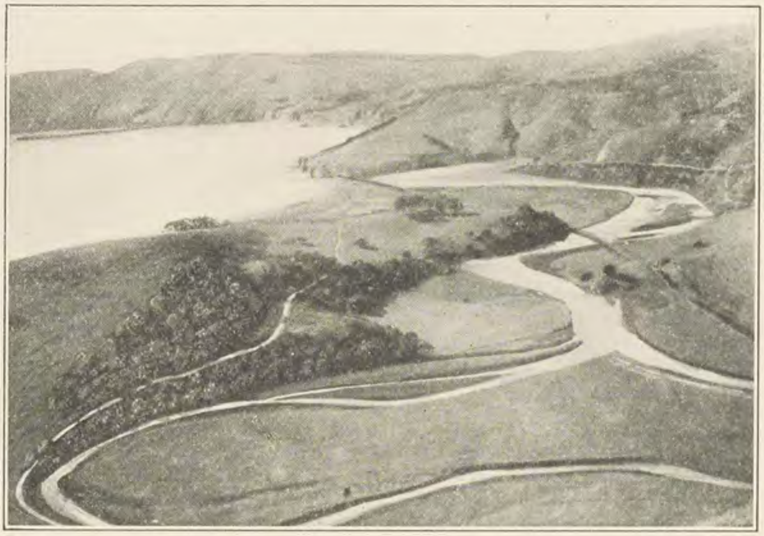

Fig. 15. Meanders near mouth of San Luis Obispo Creek, California, looking west across the bay

In the foreground a meander has been cut off, forming an oxbow. Across the bay is San Luis Hill, leveled off by ocean waves during the Pleistocene, now elevated seven hundred feet above sea level. (Courtesy of the United States Geological Survey)

The development of meanders. When a river has nearly completed its downcutting, so that the slope of its bed is just sufficient to enable it to carry its load, it may still wear on the outer side of every turn and thus continue to broaden its valley until it swings in curves appropriate to its volume. Such curves in a stream are called meanders (Fig. 15), the name being derived from the Meander, a serpentine river in Asia Minor. The meanders of a meadow brook may measure only fifty feet, while those of the lower Mississippi River are from three to six miles across.

The growth of a flood plain. As the outer bank of a curving channel is cut away the inner bank is filled up to the level of high water with mud, sand, and gravel from further upstream. There is thus developed on the inner side of each curve a level strip of loose rock waste, the flood plain (Fig. 12, *f*). This flood plain increases in breadth with the broadening of the stream channel. As the meandering stream swings against its valley walls, now here, now there, the walls will be eaten away until the resultant flood plain attains a width of many times its meander belt. The flood plain of the Mississippi River below Cairo varies in width from twenty to sixty miles. The flood plain (Mauch Chunk) deposited during the Mississippian times upon the western foot of the now largely vanished land of Appalachia covered what is now the state of Pennsylvania.

Fig. 16. Ripple marks in sandstone formed during Cambrian times

The movement of the water across the level surface of a flood plain, and especially the action of the winds in the production of waves as the waters become very shallow, give rise to numerous low, parallel ridges (*ripple marks*) in the mud and sand (Fig. 16). After the disappearance of the water the mud shrinks, forming polygonal, roughly hexagonal, blocks. The cracks separating these blocks are known as *mud cracks* (Figs. 17, 18). The ripple marks and mud cracks, during the ensuing dry summer, harden, and the cracks and depressions between the ripples become filled with wind-blown dust and sand. They thus tend to be preserved under the next overflow with its deposits of mud. The majority of fossil ripple marks and mud cracks are found in such fresh-water deposits.

Fig. 17. Mud cracks

Natural levees. When, at times of high water, the river overflows its banks, the coarsest material will be deposited where the current is first checked, that is, at the edges of the main current, while from the stagnant water upon either side of the stream a comparatively small amount of fine silt will slowly settle. In this manner there will be built up, through successive floods, a ridge of higher land bordering each side of the stream (Fig. 12, *l*). Such a ridge, called a natural levee, borders the Mississippi below New Orleans to a height of ten feet. These natural levees make it difficult for the tributaries to enter the main stream. The Yazoo is forced to travel 200 miles downstream parallel to the Mississippi before it can enter it. Artificial levees are usually built upon the natural ones to protect the lower-lying lands at times of very high floods.

Fig. 18. Mud cracks in Paleozoic limestone from Tennessee

Alluvial fans (Fig. 19). When, at the base of an elevation, a stream has its force, and hence its carrying power, lessened, both because of the abrupt change of slope and because of the change from a narrow to a wide channel, aided often by high evaporation and seepage, rapid deposition takes place. This deposition, in the form of a fan-shaped or cone-shaped structure called an alluvial fan, is composed of coarser sediment near the mountain and of finer material farther forward. The slow rate at which successive additions to the surface of such a fan are at times made is well shown in the excavation of the fans at the eastern end of Lake Geneva in Switzerland. At a depth of five feet were found ruins of Roman settlements; at a depth of from fifteen to twenty feet were Stone Age implements.

Alluvial fans frequently coalesce, forming a more or less extensive river-made plain, as at the western base of the Wasatch Mountains in Utah. When alluvial fans from neighboring mountains meet, the trunk river in the depression is pushed away from the base of the higher mountain because of the greater amount of sediment there present, due to the more rapid growth of the fans. Thus the Sacramento and San Joaquin rivers draining the central valley of California have been pushed nearer the lower Coast Range, away from the higher Sierra Nevadas (compare with Fig. 101). By a similar development the trough occupied by the Po River has been pushed nearer the lower Apennines because of the longer and higher alluvial fans of the Alps.

Fig. 19. Alluvial fan built out from a gully

Deltas. When the material carried by a stream is deposited in standing water, instead of upon land as in the alluvial fan, it forms a delta, so called because its outline tends toward that of the Greek letter delta, Δ. This difference in manner of deposition gives to the delta a different structure (Fig. 20).

The growth of a delta depends upon (1) the amount of sediment deposited by the stream, (2) the depth of the lake or sea in which it is forming, (3) the strength of the waves and currents and the stability of the delta region. At the mouth of the Rio Grande the currents are strong enough to straighten out the delta front, but they are not strong enough to do so at the mouth of the Mississippi. If the upward building of the delta cannot keep pace with the sinking of the land, the sea will drown the lower end of the river valley, forming a bay. The Delaware and Chesapeake bays give evidence that the Delaware and Susquehanna rivers could not, with their deposits, keep pace with the pronounced depression of the land; they likewise show that this depression was so recent that deltas have not yet been built. The Mississippi River, with nearly one half of the material eroded from the entire continent of North America deposited at its mouth, has been able to extend its delta rapidly, notwithstanding the slight sinking of the land indicated by Mobile Bay to the east and Galveston Bay to the west.

Fig. 20. Longitudinal section through a delta

The sediment rolled along the bottom of the stream is deposited upon the edge of the steep slope forming the inclined fore-set beds (*F*). The material in suspension gradually settles farther out, forming the flat-lying bottom-set beds (*B*). As the delta is extended seaward, the coarser material is deposited upon it, forming the flat-lying top-set beds (*T*). Most of the delta is below sea level, extending far seaward, beyond the top-set beds

When Abraham was born in Ur (2000 B.C.) the city was a seaport at the head of the Persian Gulf. It is now many miles inland, owing to the sediment brought down by the Tigris and Euphrates rivers. The united Ganges-Brahmaputra delta in northeastern India has a length seaward from the land of 200 miles, as has likewise the Indus delta in northwestern India. At New Orleans the Mississippi delta has been penetrated to a depth of 1042 feet and the bottom not reached. The Gulf of California, which formerly extended 150 miles farther northwest, has been beheaded by the growth of the Colorado delta.

The water in the beheaded portion of the gulf evaporated, and now a part of this basin floor, the Imperial Valley of California, over 200 feet below sea level, is under cultivation.

Disappearance of lakes. As delta deposits gradually fill a lake basin and the outgoing current lowers its outlet the lake becomes a swamp, frequently a peat bog, and finally dry land. Such extinct lakes, with their flat-lying sediments, are common in regions that were lately covered by glaciers, as in northern United States and Canada, and in Europe. A lake is thus a temporary structure, its existence very brief, a mere episode in the history of a river system.

GROUND WATER

A large amount of the water that falls upon the land sinks into the ground, much of it to reappear later at a lower level in the form of springs. During its very slow progress through the rocks it picks up various substances with which it may cement portions of the rock or which may appear at the surface as the chemical content of springs. Every spring has some foreign substances in solution.

Quantity of ground water. The amount of ground water depends upon the amount of rainfall and the character of the region. If the ground is covered with vegetation, the water will run off more slowly and thus have time to sink into the ground. Similarly, a level surface, other conditions being equal, will collect more than a sloping surface. Water will enter coarse soil more rapidly than fine soil. The quantity of water that a rock is capable of holding depends upon the size and number of the cavities within it,— in other words, upon the porosity of the rock. The quantity of water in a rock varies from less than 1 per cent of the weight of the rock in granites to 30 per cent in some sandstones and 40 per cent in sandy soils. It has been estimated that the total amount of ground water is sufficient to cover the earth's surface to a depth of some 3000 feet.

The upper and lower limits of ground water. The water present in the ground decreases in amount from the surface downward. The depth to which ground water may penetrate is probably not much greater than ten or twelve miles; at this depth the great pressure probably has closed all the cracks and pores of the rocks, just as the stamping of a die compresses metals. The upper surface of ground water depends upon the balance between the amount of water taken into the rocks and the amount lost through evaporation and springs. This surface, the level of underground water, or the *water table,* as it is called, lies just at the surface of the ground in swamps and above it in lakes (Fig. 22).

Wells. Most ground water is in constant though slow motion. Observation has shown that in coarse sand it moves at the rate of about one mile a year; hence its movement must be very slow in fine-grained rocks. Thus, when a well is sunk into ground water, the water gradually flows in from all sides to take the place of that removed by pumping; this movement interrupts locally the normal, one-direction flow of the ground water in that region (Fig. 21). This local change in the flow of the ground water near a well is subject to the same principle as that when the normal flow of air in the United States toward the northeast is interrupted by our ordinary cyclonic storms and the air rushes from all directions to fill up the low-pressure area.

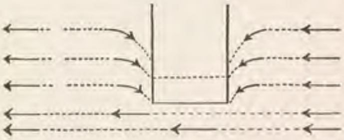

Fig. 21. Diagram to illustrate why pumping water from a well and consequently lowering the water level deflects the regular flow of underground water

Springs. After a rain the water quickly sinks into a sandy soil but lies long upon a soil of clay, where most of it disappears through evaporation. Thus a clay bed is relatively impervious, while sandstones are the principal water bearers. Where the surface of the land cuts the zone of underground water, springs result. If this land is of unconsolidated material, such as soil, there results merely a general oozing out of the water, a seepage spring such as is shown in Fig. 22 at *Se–Se′*. If there is a solid, porous rock, like sandstone, underlain by a relatively impervious bed, such as clay, the water flowing down the slope will issue as a spring at the top of the impervious bed (at *S* in

Fig. 22). This is the most common type of spring. Another common type is the fissure spring. If the water flowing down a porous bed between two impervious ones encounters some fissure through the impervious bed, it will enter this, and if the pressure of water is sufficiently strong, it will issue as a spring, as at *FS* in Fig. 22; this is a natural artesian well.

Springs are likewise common in limestones. Here the water, seeping along cracks and bedding planes in the rock, enlarges its passageway by dissolving the limestone. Thus in time are formed large underground passages from which issue some of the largest known springs. In Tennessee are many such springs.

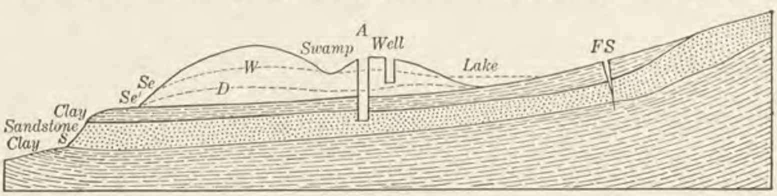

Fig. 22. Vertical section to show underground-water conditions

The dotted lines indicate the lowering of the upper surface of the ground water (that is, the water table) from wet (*W*) to drought (*D*) conditions. During this change the lake becomes a swamp, the swamp becomes dry land, and the well goes dry. The water table rises in the hills. There is seepage at *Se–Se'*. A spring (*S*) of the ordinary type occurs at the contact of the porous sandstone and the impervious clay bed below. *FS*, a fissure spring; *A*, an artesian well

Artesian wells. Rain falling upon the soil in any area descends with comparative rapidity to the surface of the underground water, upon which it presses, urging the water from beneath it. This hydrostatic pressure may become very great, especially when it is confined in a porous rock between impervious beds, so that if a deep well is sunk into this porous bed the water may be forced up hundreds of feet to the surface. Such a well, sunk deep into the earth, whether flowing or not, is called an artesian well (Fig. 22, *A*).

Geysers. When water sinking into the earth comes into contact with very hot rock, it is apt to be forced to the surface through some fissure. Such eruptive hot springs, or geysers, are today almost wholly confined to Iceland, New Zealand, and the Yellowstone National Park of the Rocky Mountains. If the fissure tube through which the water rises to the surface is surrounded by hot rock from the level of the ground water downward, steam will rush forth continuously. If, however, the heat is greatest at the bottom of a long tube, the base of the water column will arrive first at the boiling-point, and the expansion of this will push some of the water as an overflow out of the top of the column. The consequent decrease of pressure will cause that portion of the basal water column which was at boiling-point except for the great pressure to burst into steam and thus force the entire water column above into the air (Fig. 23).

Fig. 23. A geyser in the Yellowstone National Park

Chemical work of ground water. As water moves through the ground its solvent action causes it to pick up such elements as it can dissolve. Of all the elements which enter largely into the formation of rocks, lime is most readily dissolved by ordinary terrestrial waters. Thus caverns are readily formed in rocks composed chiefly of lime. Limestone caverns of such origin, like the Mammoth Cave of Kentucky and Adelsberg Cave south of Laibach in Jugoslavia, are of common occurrence in regions underlain by limestone.

When all but one portion of the roof of a cavern collapses, a *natural bridge* results. Beneath its arch still runs the stream, whose ancestral waters formed the original hollow. This is the most common way in which natural bridges are formed (Fig. 24).

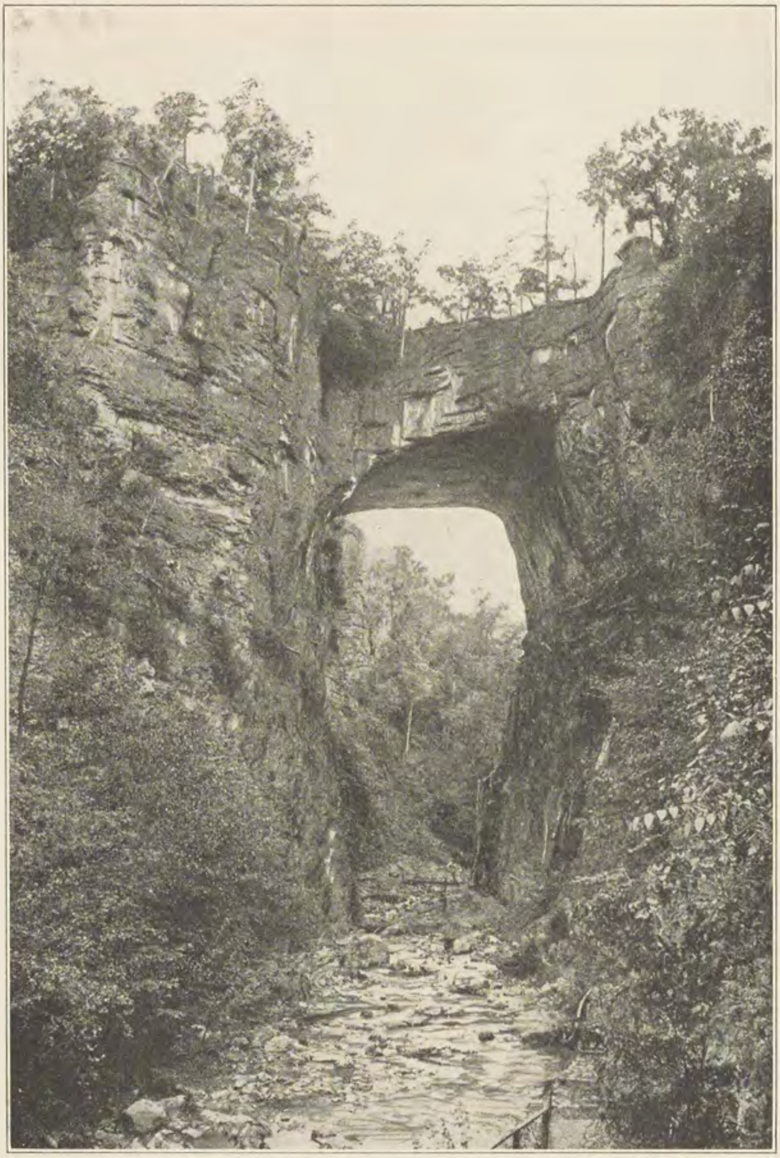

Fig. 24. The Natural Bridge, Virginia

As ground water oozes through cracks in the limestone roof of a cave it becomes saturated with lime; and as soon as it emerges from the rock, relief of pressure and evaporation cause the deposition of much of the dissolved lime. That part hanging like icicles from the roof forms *stalactites,* while that which rises conelike from the floor, built up by the limewater that drips from the tips of the stalactites, forms *stalagmites*; these roof and floor projections may grow together into columns.

Fig. 25. A sectioned geode, showing the quartz crystals within

Many substances besides lime may be deposited in small cavities where the ground water oozes into them. Quartz, iron, lead, zinc, etc. may form *veins* (long, narrow deposits) or *geodes* (rounded and usually but partly filled cavities) (Fig. 25). When the excess of matter in solution is aggregated about some center within unconsolidated or solid rocks, *concretions* are formed. This aggregation may be pure, as the flint nodules found in chalk, or it may incorporate particles of the rock matrix, such as clay or sand, which appear in the stratification planes passing through the concretion. Concretions may vary in size up to several feet in diameter (Fig. 26). If the material in solution replaces the wood, lime, etc. of organisms, *petrifactions* are formed.

Thus the chemical work of underground water may result in a subtraction of mineral matter, as in cavern formation; in an addition, as in the formation of stalactites, veins, geodes, and concretions; in new mineral combinations, as in the hydration of minerals (see page 43); or in a substitution of mineral matter, as in petrifactions.

SUMMARY OF STREAM EROSION

The importance of rainfall to life is evident. An annual rainfall of 20 inches is usually the necessary minimum for agriculture. The warmer the climate, the more rain is needed. The great importance of rainfall in the destruction of the land areas of the earth is not, however, so self-evident.

Fig. 26. Large concretions exposed by weathering in the late Cretaceous sandstone (Laramie) near Newcastle, Wyoming

Courtesy of the United States Geological Survey

It is estimated that over 29,000 cubic miles of rain falls each year upon the land of the earth. A part of this amount is evaporated, a part sinks into the earth, while the remainder, some 6500 cubic miles, runs off, forming streams. Both the water that sinks into the earth, to reappear as springs in lower land or beneath the ocean surface, and that which forms streams aid in carrying land to the ocean in solution. A cubic mile of river water carries on the average 420,000 tons of foreign matter in solution. That is, the run-off of the land thus carries to the ocean annually almost 2,750,000,000 tons of solid substances in solution, about 50 tons per square mile a year (Clarke). The erosion of the land is due principally, however, to the matter which the streams carry in suspension. The Mississippi River carries annually into the Gulf of Mexico 113,000,000 tons of matter in solution and 406,000,000 tons of matter in suspension, and rolls along its bottom some 5,000,000 tons of sediment. From many years of stream-gauging by many workers throughout North America it has been estimated that there are removed to the ocean from the United States annually 270,000,000 tons of dissolved matter and 513,000,000 tons of suspended matter (Dole and Stabler).

TOPICAL REVIEW

- The wearing down of the land
- Disintegration of the solid rocks
- Development of streams and their valleys
  - Rapidity of stream erosion
  - Features due to stream erosion
  - An erosion cycle
    - Youth, maturity, old age
  - Growing old may be hastened or retarded
- Deposition through stream erosion
  - Causes of deposition
  - The development of meanders
  - The growth of a flood plain
  - Natural levees
  - Alluvial fans
  - Deltas
  - Disappearance of lakes
- Ground water
  - Quantity of ground water
  - The upper and lower limits of ground water
  - Wells
  - Springs
  - Artesian wells
  - Geysers
  - Chemical work of ground water
- Summary of stream erosion

CHAPTER VI

GLACIERS AND THEIR WORK. THE WORK OF WINDS

GLACIERS (RIVERS OF ICE) AND THEIR WORK

Snow line. In the higher latitudes and altitudes a part of the moisture of the atmosphere falls in winter as snow. Much or all of this melts during the succeeding summer, but in regions where the snowfall has been greater than can be melted in the summer, snow fields remain throughout the year. The lower limit of perennial snow fields, that is, the snow line, passes from an altitude of about 18,000 feet in the tropics, through decreasing heights, to approximately sea level in Arctic regions.

Change from snowflakes to solid ice. Snow quickly passes from its originally soft, loose, fleecy-white condition to a coarse-grained state, the *névé*, to porous ice, and finally to solid bluish ice. An early stage of the granular state is well seen in remnants of snow banks in spring. Snowflakes are white because the crystals of water vapor are separated by air; soap bubbles are white for the same reason. As snow increases in thickness the pressure expels some of the air from between the snow crystals, the growth of the snow crystals expels more air, while the seeping in of water and its freezing continue the process to solid ice. In such ice the crystals are oriented at all angles to the surface, for they fell thus as snow. Ice formed on a pond has a columnar structure, the long axis of each crystal extending downward from the surface, as it was in this way that additions to the thickness of the ice were made.

Movement of glaciers. As snow and ice increase in thickness the pressure between some ice crystals will finally produce sufficient heat to cause melting at the points of exceptional pressure. The water thus formed will flow, usually down the slope, to regions of less pressure, a fraction of a millimeter distant, and there freeze; in freezing it expands and hence exerts a pressure upon the surrounding ice. Water in freezing expands one tenth of its original volume and exerts a pressure of 150 tons to the square foot. The result of an innumerable number of such expansions is to push the ice down the valley, partly by causing those ice crystals which lie in the direction of greatest pressure to slip along their gliding planes and partly by pushing forward the whole mass. In this way movement of the entire ice mass takes place from regions of greater to those of less pressure, that is, down the slope of the land. The resultant streams of ice are called glaciers (Figs. 27, 29). Since the melting of only minute particles occurs at any one time, the ice remains solid, rigid, brittle, and crystalline at all times. Movement of the ice is naturally greatest when it is warm and wet. The Mer de Glace in Switzerland moves about twenty-seven inches a day in summer and but half this distance in winter. Glaciers vary in rate of movement from one to two feet a day in the case of the small mountain-valley glacier to sixty or more feet a day for such large glaciers as those of northern Greenland. The movement of the various portions of a glacier is like that of the water of a river (Fig. 28).

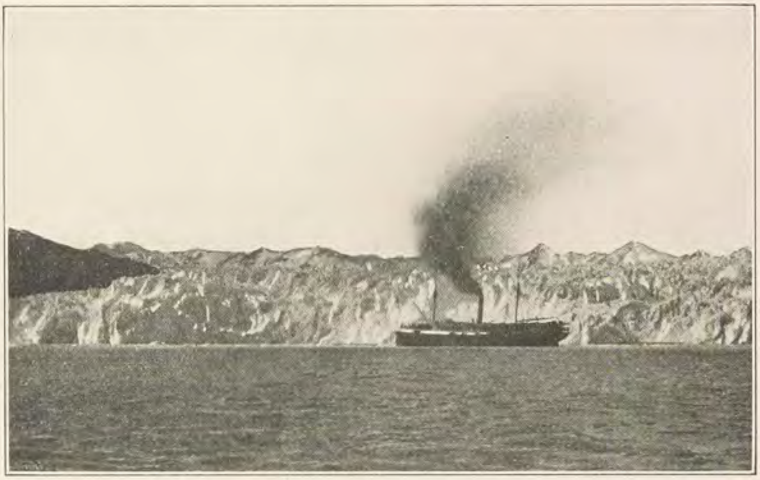

Fig. 27. View of the front of Columbia glacier, Prince William Sound, Alaska

When the slope of the rock bed over which the glacier moves is abruptly increased, even though by only two or three degrees, it causes the glacier above to crack and yawn, producing fissures. Such fissures, called *crevasses,* may have any size up to a width of 20 feet and a depth of 100 feet or more. The occurrence of crevasses where the change of slope is slight is evidence that the ice does not move as does a viscous substance like tar, and is similarly evidence against the hypothesis that its forward movement is due to regelation, that is, to minute fracturing and refreezing.

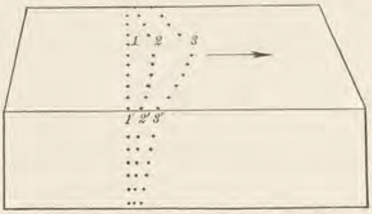

Fig. 28. Diagram to illustrate movement of ice in a glacier

Movement is in the direction of the arrow. A line of stakes across the glacier at *1* occupied in successive months positions *2* and *3*, while the corresponding movement of the ice in depth took positions *1′*, *2′*, *3′*, thus indicating movement to be fastest in the middle top area, or, in the case of a curve, near the outer edge. In one case, while the surface of the glacier moved six inches, the middle moved four and a half inches and the bottom two and a half inches

Size of glaciers. As the size of a river depends principally upon the amount of precipitation within the area drained by it, so likewise does the size of a glacier. As a stream rising in a mountain and emerging upon a dry plain rapidly disappears under the unfavorable condition of aridity, so a glacier rising in a mountain rapidly disappears under the unfavorable condition of warmth with lower altitude. In both the water stream and the ice stream the lower limit is a balance between the forward motion and the dissipating forces of evaporation or melting. The surface of alpine glaciers is lowered from 18 to 25 feet during a single summer. Thus it is that the large glaciers are found in the moister portions of the colder polar regions. Glaciers vary in size from small ones of a quarter of a mile in length in steep mountain regions to the one which, larger than Europe, covers the entire Antarctic continent.

Types of glaciers. When the surface upon which glaciers are being formed slopes in all directions, it initiates a resultant ice motion in all directions. *Ice caps* thus formed may be small, as on some promontories in Greenland and Iceland, or large, like the one which covers most of Greenland. When an ice cap covers a large part of a continent, it is called a *continental glacier*. The Antarctic ice cap is a present-day example, while in the recent past, in the Pleistocene period, such continental glaciers covered much of northern North America and northwestern Europe. Ice caps naturally develop ice tongues near their margins, which then become *valley glaciers*. Valley glaciers in high mountains may or may not arise from ice caps. Such mountain glaciers are usually called *alpine glaciers* (Fig. 29).

Fig. 29. View of the Rhone glacier, Switzerland

Note the cirque at its head

Icebergs. When a glacier enters the sea over a cliff, the ice breaks off in large masses, which, falling into the sea, become icebergs. If, however, the glacier enters below sea level, the ice will be buoyed up until it breaks off, forming very large icebergs. Thus icebergs naturally vary much in height as well as in breadth. The average height of those developed from the Greenland glacier is about 800 feet, 100 feet of which is above sea level, seven eighths of the berg being below sea level. In

Antarctic waters icebergs over 500 feet high have been reported; such height above sea level would mean a total height of 4000 feet. In breadth they vary up to a quarter of a mile or even more, though the vast majority are smaller. Since icebergs are formed upon land, they are composed of fresh-water ice. The frozen surface of the ocean usually yields thin floes, a few feet in thickness.

Erosion by glaciers. Since the snow partially surrounds many rocks and is frozen fast to projecting points of others, it naturally carries this attached material with it when it begins to move forward as a glacier. As it moves, the pieces of rock projecting from the base of the glacial ice, in which they are held as in a vise, scrape and grind the rocks over which they pass, thus still further deepening the developing valley and adding to the rock fragments which are being transported. The valley floors and sides are thus grooved by bowlders and pebbles, and polished by sand and rock powder. At the same time these bowlders become similarly flattened, polished, and grooved, as is shown by the glacial striæ which they carry on their surfaces (Fig. 30). Where the rock is jointed

Fig. 30. Two small bowlders from the Pleistocene till of Massachusetts, showing glacial striæ

especially upon the lee side of a slope, a plucking out of rock fragments is very apt to occur.

Cirques. In a mountain glacier, erosion at its source is quite pronounced, producing an amphitheater-like depression called a cirque (Figs. 31, 32).

Fiords. It follows that the greatest effects in glacial erosion occur in the valley glaciers which extend outward from large continental ice caps. In such places deep, narrow valleys are gouged out. Such valleys, when later entered by the ocean, become long, narrow bays bordered by steep, rocky walls, and are known as fiords. Fiords formed thus during the Pleistocene glacial period abound in Norway, Scotland (known here as sea lochs), Labrador, British Columbia, southern Chile, and New Zealand.

Hanging valleys. Small tributary glaciers enter the main glacier with an even surface, just as tributary water streams enter a river. Unlike the river, however, the glacier, because of its much less fluid state, cuts rapidly sidewise as well as downward, so that a cross section of its valley is U-shaped, in contradistinction to the V-shaped valley cut by a river. Its small tributaries cannot cut as deep as the main glacier and hence they enter high above its rock-floor bed. After the ice has disappeared, the streams in these tributary hanging valleys must enter the main valley as falls (Fig. 33).

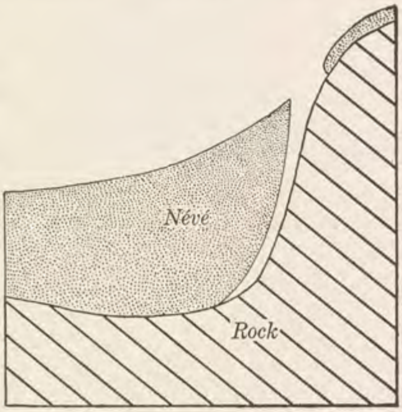

Fig. 31. Development of a cirque

Erosion here takes place most rapidly at the bergschrund, which is the crevasse formed between the head of the glacier, composed of névé, and its rocky wall. This may vary in width from two to eighty or more feet. It is the scene of the most rapid thawing under the sun's rays by day and of freezing by night. The melted water extends the thawing to the base of the bergschrund and, entering all rock cracks, freezes, with consequent further disruption of the rock. This freezing and the weight of the annually increasing snow force the rock fragments thus formed down the valley. Thus especially rapid erosion through plucking takes place at this point, giving rise to an amphitheater-like hollow, the cirque

Deposition by glaciers. Thus the glacier bears within it rock fragments plucked from the cirque area and from the sides and bottom of its bed. Upon it is also gathered a load; for, as the glacier moves down the valley, avalanches and warm-weather freshets add rock débris to its margins. These two lines of marginal débris are known as *lateral moraines.* Thus, rasping and plucking, grooving and polishing, the glacier moves down the valley with its heavy load of rock fragments beneath, within, and upon it.

Moraines. When the forward movement of the glacier is just balanced by the melting of the surface and front, its terminus remains stationary. As a consequence the principal portion of its load is dumped at this place for as long a time as the terminus remains here, since the ice continues to move forward although the terminus is stationary. These deposits, forming the *terminal moraine,* rise in a series of hills, knobs, and ridges with depressions between, called kettles (Fig. 34). Terminal moraines vary in thickness from 2 or 3 feet to 2000 feet. Above the plain of the Po River, southeast of Mont Blanc, they reach a height of over 1000 feet.

Fig. 32. View of five cirques on the eastern face of Cascade Mountain, Alberta, Canada

Note the horizontal bedding of the Paleozoic strata. (Photograph by H. W. Shimer. Courtesy of the Geological Survey of Canada)

When, at the coming of a warmer climate, a valley glacier disappears, the melting back of the glacier is nearly always accomplished in alternating stages of advance and retreat, the

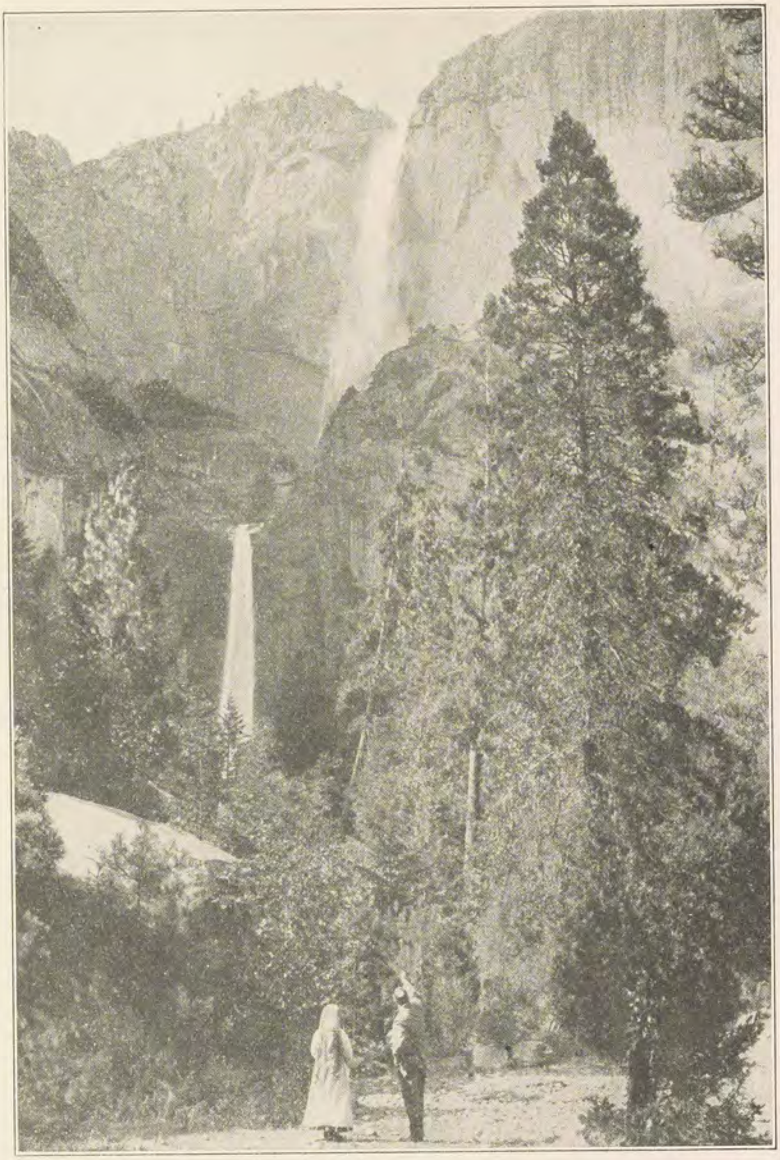

Fig. 33. View of Yosemite Falls (descending from a hanging valley), Yosemite Valley, California

Fig. 34. "Knob and kettle" topography

The map shows a portion of the terminal moraine which forms the backbone of Long Island. The kettles are indicated by contours with inwardly directed short lines. To the south of the moraine is the beginning of the outwash plain developed at the time of the melting of the glacier. This plain descends with a gentle slope beyond the area of the map to Jamaica Bay (a lagoon), which is bounded seaward by Rockaway Beach (a barrier beach). (United States Geological Survey sheet, Brooklyn. Scale: 1 inch = 1 mile; contour interval = 20 feet) advance in each case being less than the retreat. Thus a succession of terminal moraines, or, more properly, *recessional moraines,* are formed behind the main terminal moraine. Upon the melting away of a valley glacier its lateral moraines will be lodged upon the valley sides, often high above the valley floor. The rest of the material which is borne beneath, within, or upon the glacier will be let down at whatever points the melting may take place, thus forming the *ground moraine.*

Fig. 35. Perched bowlder on a glaciated rock surface, north of Bloods, Calaveras County, California

Photograph by Turner. Courtesy of the United States Geological Survey

Perched bowlders. If large bowlders are present in or upon the glacier, these may be left, after the melting of the glacier, perched upon the tops or sides of hills. While the majority of these bowlders are so unstable as soon to roll down into the bottom of the valley, a few remain as perched bowlders or rocking stones, testimony to the former presence of glaciers over the region (Fig. 35).

Glacial lakes and kettles. Kettles are comparatively small depressions in glacial deposits. Such depressions are due at times to the irregular dumping of the material and at times to the irregular rearrangement of a terminal moraine by a slight readvance of the glacier. They seem to have been formed usually by the slow melting out of sediment-covered blocks of ice as the glacier retreated.

Since the terminal moraine is concave toward the glacier, as may be noted in the position assumed by a line of stakes upon a moving glacier (Fig. 28), it is apt, unless it is trenched by a stream, to hold a lake back of it. Such is the origin of many lakes in northern North America and Europe. In many cases the last recessional moraine formed just before the disappearance of a glacier from its cirque holds such a lake. Frequently also kettles hold small lakes.

Drumlins. When surface melting renders the glacier too light to be able to continue pushing the load beneath it, it rides up over the dropped material, elongating it in the direction of movement of the glacier. These deposits, thus modified into drumlins, correspond to the sand bars in a stream. In both cases the decreased power of the carrying agent gives rise to the deposit, and the motion of the stream determines its shape. Drumlins were abundantly formed during the melting back of the late continental glacier from North America. In Wisconsin, New York, and New England they are very numerous. Most of the islands in Massachusetts Bay are drumlins (Fig. 36).

Deposition by glacial waters. The stream pouring from the front of a glacier in its melting deposits its load of sediment down the valley; and since it carries much sediment, it must drop some of it as soon as the grade lessens. A glacial stream thus tends to build up its valley instead of eroding it. Since the summer is the time of maximum melting, it is consequently the time of maximum carrying capacity and hence of coarser deposits. Thus for each year there is a bed of coarser material, grading upward into finer, just as there is in our common trees a yearly ring of coarser spring cells grading outward into finer summer ones (Fig. 113).

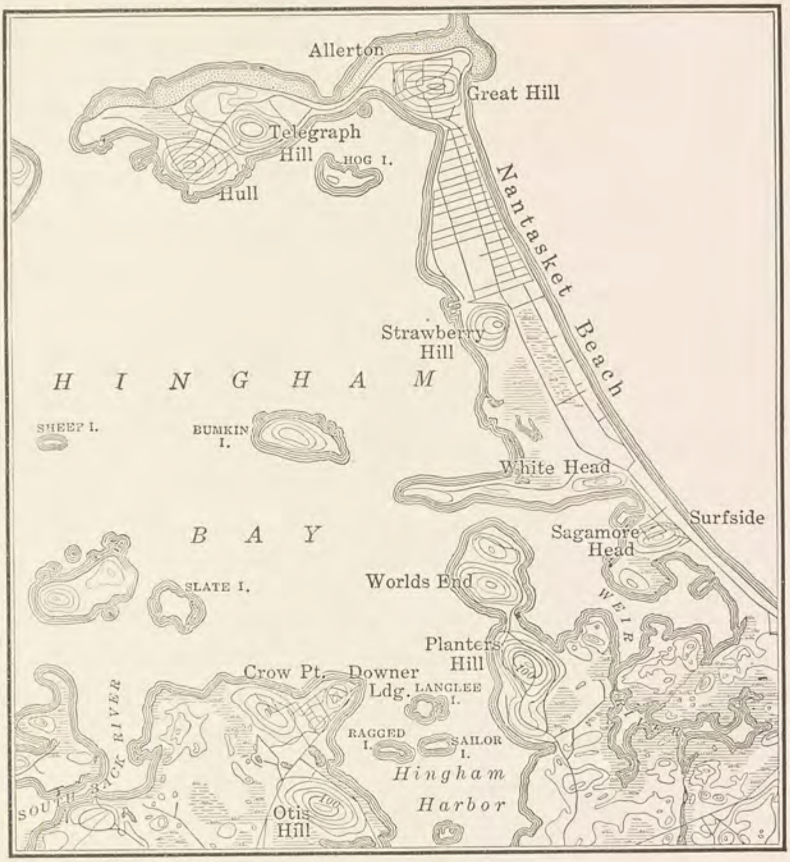

Fig. 36. Drumlins and land-tied islands

Nantasket Beach is a sand reef uniting three drumlins to one another and to the mainland to the south. The steep eastern side of Strawberry Hill shows that one half of the hill had been eroded by the ocean waves before the beach had developed. Otis Hill and the two hills at Worlds End are likewise typical drumlins. (Part of the United States Geological Survey sheet, Boston Bay and Vicinity. Scale: 1 inch = 1 mile; contour interval = 20 feet)

If the glacial stream enters a lake, a delta will be formed with typical top-set, fore-set, and bottom-set beds (Fig. 20). Upon the disappearance of the glacial lake the delta becomes a *sand plain*. The deposits in the channels which streams had cut for themselves in or beneath the glacier are known as *eskers*. These fossil stream beds resemble artificial railway embankments.

Summary of glacial deposition. The material transported by a glacier is deposited under two forms, both commonly known as drift. That part of it which is dumped by the ice, called *till* or *unstratified drift,* is naturally laid down without any sorting, the mud, sand, and bowlders all together. There are accordingly in these deposits no bedding planes. To this class belong moraines, drumlins, and perched bowlders. That part of the material which is deposited by the water from the melting of the glacier is called fluvioglacial deposits or *stratified drift*; it is more or less sorted by the water and is thus deposited in beds, or strata. Such are sand plains and eskers.

Effects of continental glaciation. A region subjected to widespread glaciation will have its preglacial river systems deranged; for the glaciers will tend to fill with rock débris those valleys that are transverse to its movement, and to deepen and widen the valleys parallel with its movement. The glacial deposits will frequently force the streams to cross old divides and hence to form falls, will bring about the formation of numerous swamps, ponds, and lakes, and will produce the typical glacial "knob and kettle" topography (Fig. 34). In brief, the effect of continental glaciation upon drainage will be to renew its youth. Its effect upon the bed rock is to remove all partly decomposed material, and thus glacial deposits will come to rest directly upon solid polished rock, — a succession not found in regions beyond the extension of the glaciers, where the soil changes gradually downward through rotten rock to solid rock.

THE WORK OF THE WINDS (STREAMS OF AIR)

The atmosphere surrounding the earth acts as a blanket to keep the earth warm, since many of the sun's rays are trapped by it. One result of this heated atmosphere is wind. As wind moves over the surface of the earth it produces a pressure through which mechanical work is done. This pressure may become so great, as in hurricanes and cyclones, as to demolish houses and uproot trees. Picking up sand and using it as a tool, the wind may in time produce tremendous effects; it may carve such fantastic rocks as are in the Garden of the Gods in Colorado. (Application of this principle has led to the use of the artificial sand blast for etching glass and stone.)

In arid regions, especially those with an annual rainfall of less than five inches, numerous small and large shallow basins are eroded under the combined action of rock breakage through the great daily changes in temperature, due to the lack of the heat-conserving moisture, and the strong winds that carry away these broken rock particles. In the southwestern part of the United States such depressions are called tanks, since they often hold water for some time after a rainfall.

Fig. 37. Sand dunes in the San Luis Valley, Colorado

The sand blown by the wind moves up the gentle slope and falls over the steep edge, thus causing a forward movement of the dune in this direction. (Photograph by Siebenthal. Courtesy of the United States Geological Survey)

The finer material carried by the wind will, after innumerable halts, become lodged in a river, lake, or ocean or over some damp region covered with vegetation. In such grass-covered areas it is held by the bases of grass stalks and may accumulate without bedding planes to a great thickness. Such yellowish-brown deposits, the *loess*, are common, as in the upper Mississippi Valley, the Rhine Valley, and north-central China. Fine dust has aided greatly in burying the remains of ancient civilizations, such as the Babylonian and the Roman. The coarser particles, which the wind is unable to lift to a great height, are usually rolled along the ground until stopped in the lee of some object. This causes the lodgment of more sand until a mound, or *sand dune*, is formed (Fig. 37). Dunes, which usually reach heights of from 10 to 20 feet, or, in exceptional cases, of 300 feet, are abundant along the sides of braided streams, as the Platte River and its branches, along lakes and seashores, and in desert regions; in other words, they are found wherever fine material is sufficiently loose to be rolled along by the wind. Fossil sand dunes, with their characteristic cross bedding, are very numerous, though today, as during the past history of the earth, the wind is of much less importance in the formation of strata than is water.

TOPICAL REVIEW

- Glaciers (rivers of ice) and their work
  - Snow line
  - Change from snowflakes to solid ice
  - Movement of glaciers
  - Size of glaciers
  - Types of glaciers
  - Icebergs
  - Erosion by glaciers
    - Cirques, fiords, hanging valleys
  - Deposition by glaciers
    - Moraines
    - Perched bowlders
    - Glacial lakes and kettles
    - Drumlins
  - Deposition by glacial waters
  - Summary of glacial deposition
  - Effects of continental glaciation
- The work of the winds (streams of air)

CHAPTER VII

THE OCEAN AND ITS WORK. SUMMARY OF DEPOSITION

Of all the water gathered by the earth upon its surface the ocean is the great final reservoir. This is the primary source as well as the ultimate goal of all rain.

Of the 197,000,000 square miles of earth surface the ocean today occupies 143,000,000 and the land 54,000,000; in other words, about 72 per cent of the surface of the earth is covered with ocean waters. The average depth of the ocean is 12,500 feet, while 4 per cent of it has a depth ranging from 18,000 to 30,000 feet. The greatest known depth (32,636 feet) is 150 miles southeast of Tokyo, Japan. In contrast the average height of the land is 2000 feet, and the greatest height (29,141 feet) is that of Mount Everest of the Himalaya Mountains.

COMPOSITION OF OCEAN WATER

As the water runs from the land into the ocean it carries with it much material in solution. Some of this material, notably calcium carbonate, is extracted from the water by animals in their life processes, other materials unite with depositing sediment, while still other substances, especially sodium chloride, have kept increasing in ocean waters throughout earth history. Average sea water at present contains three and a half pounds of solid matter to each hundred pounds of water.

Of one hundred pounds of this solid matter, approximately

78 pounds = sodium chloride ($NaCl$)
11 pounds = magnesium chloride ($MgCl_2$)
5 pounds = magnesium sulphate ($MgSO_4$)
4 pounds = calcium sulphate ($CaSO_4$)
2 pounds = potassium sulphate (K_2SO_4)
0.2 pound = magnesium bromide ($MgBr_2$)
0.3 pound = calcium carbonate ($CaCO_3$)

The last item includes all traces of other salts, such as copper (Cu), gold (Au), iodine (I), manganese (Mn), phosphorus (P), and silicon (Si). Dissolved in ocean water are also oxygen (O), nitrogen (N), and carbon dioxide (CO_2), the last-mentioned being estimated at eighteen times the amount present in the atmosphere.

The color of ocean water is largely a consequence of its composition. The more saline tropical waters are blue, like the Mediterranean Sea and Gulf Stream, while less saline colder waters, such as the Labrador Current, are green.

DEEP CIRCULATION OF OCEAN WATERS

This great body of water is acted upon by the gravitative attraction of the earth and of the moon and sun, and also by the forces generated by the heat of the sun.

Massive movement. The gravitation of the earth draws the water within its lowest basins. This pull is naturally modified by the counter attraction of the neighboring high lands. Thus, drawn by the high Himalayan mountain mass, the Indian Ocean is 300 feet higher, that is, farther from the center of the earth, at the head of the Bay of Bengal than at the southern end of the Indian peninsula.

The effect of the moon upon the earth is greater than that of the sun because it is nearer to it. The inequalities of the attraction of the moon upon different parts of the earth result in differential elevation of the earth's surface,— the tides. The sun has similar though much weaker effects. Since tides in solid rock are negligible, their effect upon the ocean is to draw the water alternately away from and against the shores of the land. Upon the open ocean the tide moves as a broad, unnoticeable bulge, but in shallow waters it moves forward as does a wave. In mid-ocean, lunar tides have a height of about 3 feet. Their height on shore depends upon the shape of the land. In Massachusetts Bay their height is about 10 feet; in the triangular Bay of Fundy, Nova Scotia, it is over 50 feet.

Movement due to increased salinity through evaporation. The effect of the sun's heat in the movement of ocean waters is manifold. The greater amount of heat received in the tropics causes an expansion of the waters in these regions. The consequent lessening of their weight is overbalanced by the intense evaporation, resulting in increased salinity, especially in the horse latitudes, and hence in increased density of the water. As a result the tropical waters tend to sink.

Movement due to increased density through cold. At the poles, on the other hand, the greater cold causes a contraction of the ocean water and an increase in density down to 28° or 30° F., depending upon its salt content, and at this temperature it expands and solidifies. When frozen it floats and thus protects the water beneath from further decrease in temperature. (Fresh-water ice is nine tenths as heavy as the fresh water.) Since the maximum density of polar waters occurs at about 29° F., this is the temperature of most of the waters settling to the ocean floor in polar regions. Since these polar waters are today about the densest of all ocean waters, they creep over all deep ocean floors, gradually warming as they go. In the tropics such abyssal waters have a temperature of about 35° F. but are still heavier than the more saline surface waters and hence push beneath them. Thus the principal movement of ocean waters today is downward in polar regions and upward in the tropics.

It is therefore evident that the chief cause of deep-sea circulation is the pull of gravity drawing down the polar waters which are made heavy by the cold. This circulation is aided by the tendency of the heavy saline tropical waters to sink and by the great tidal movements. It is likewise furthered by the movements caused by the piling up of huge masses of fresh water brought in by rivers, as well as by the piling up of the ocean waters against the land by the winds. A two-foot rise of ocean level due to winds is common.

SURFACE CIRCULATION OF OCEAN WATERS

Waves. A swell developed by throwing a stone into the water or by the passage of a boat through it causes each particle of water to move in a closed circle, out from the zone of disturbance and back to it. As it is pushed outward by the boat it in turn pushes the water next to it, and as it returns the latter returns also. As the force moves away from the zone of disturbance this process is repeated over and over, each time with declining power. If the height of the swell or wave formed is 10 feet, the diameter of the orbit of each moving particle of water in it is 10 feet. Hence, when the surface particles are at the base of the circle, a trough is formed; when at the top, a crest. The crest of the wave has a forward motion of from 10 to 30 and even 60 miles an hour, yet the water itself is almost stationary; if it were not, ships would be thrown upon land and the seas would be unnavigable. Waves propagate themselves not only outward but also downward, everywhere with declining strength, though many waves have sufficient force to move gravel at a depth of 150 feet.

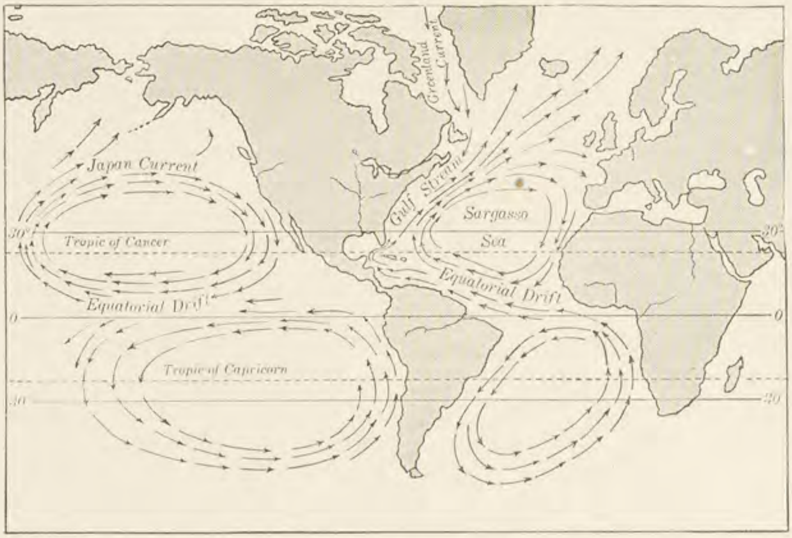

Fig. 38. Map showing main ocean drifts and currents

These circulate, in general, around the permanent areas of descending air currents, about 30° north and south latitude (p. 36). Their direction is modified locally by the contour of the continents

On a sloping shore a wave with a diameter of 10 feet will strike bottom where the water is 10 feet deep. At this point its base is slowed up while its crest moves forward, forming *breakers*. Strong waves, those with a great diameter, naturally break farther from shore than do weak ones. The forward-moving water from the breakers rushing far up the beach returns as the *undertow*.

In the case of wind-made waves the wind, being in continuous operation, causes both the undulation and the water to move forward, the former naturally much faster than the latter. Each particle of water here moves forward on the crest of the wave and backward in the trough, but the advance is greater than the backward motion. This excess of advance over return is the basis of ocean currents.

Ocean currents. Where the wind is continuous, as in the case of trade winds, there is a constant urge of the surface water in one direction, resulting in this case in the westward equatorial drift. The westward movement of this drift causes a piling up of the waters against the eastern side of intervening continents. These piled-up waters find relief to the north and south, producing the ocean currents of temperate latitudes; such are the Gulf Stream of the North Atlantic and the Japan Current of the North Pacific. The direction of these currents of temperate latitudes is modified by the borders of the continents and especially by prevailing winds (Fig. 38).

EFFECTS OF THE MOVEMENTS OF OCEAN WATERS

The constant movement of the ocean waters has far-reaching results. (1) It keeps the vast ocean pure and health-giving instead of stagnant and disease-breeding. (2) The downward-moving waters carry oxygen, which enables animals to live in the ocean depths. (3) The movement of the abyssal waters, though exceedingly slow, tends to smooth out whatever material falls there, such as very fine dust, which can be carried far by the higher winds, and the dead bodies of the microscopic plants and animals that lived at the surface of the ocean. (4) But it is especially at the margins of the oceans, where the waves strike the land, that the work of ocean waters becomes most pronounced. In such areas the land is being rapidly torn down, and the waste thus produced is carried elsewhere and serves as building materials for new lands. This is the principal destructive and constructive work of the ocean.

Destructive work of ocean waves. The destructive work of the ocean waves is practically limited to the very narrow zone affected by the breakers. Their work here is mainly accomplished by the cobbles and pebbles which they carry, though the weight of the hurled water itself is also effective. Rock masses up to fifty tons are easily moved by heavy breakers; with such tools the waves batter the rocky headlands, cutting them back into sea cliffs and leaving a rock-strewn terrace behind (Fig. 39).

Fig. 39. Wave-cut terrace, Winthrop, Massachusetts

The waves are here cutting into the unconsolidated sediments of a drumlin, Winthrop Great Head. The bowlder-strewn terrace in the foreground, developed by this erosion, is covered by the ocean waters at high tide

Wherever the land is less resistant it will be eaten into until a balance is developed between the strength of the waves and the width of the indentation. The land may be weak because formed of loose sands, of jointed rock, of an alternation of soft and hard rocks, or of rock that is easily dissolved. In this way the less resistant rocks may be worn into broad *coves*, narrow *sea caves*, etc.

Thus, like a great saw, the margin of the ocean cuts into the exposed land at the same height all over the world. Whenever the level of the ocean is changed, it is here recorded. For example, the western coast of Norway is in most places bordered by a belt of lowland from 3 to 10 miles wide. This is an old wave-cut terrace, developed when the land stood 300 feet lower than at present. On this terrace most of the population of western Norway now live. Rocky hills on this lowland represent old islands of resistant material. Such evidences of elevated lands are common throughout the world.

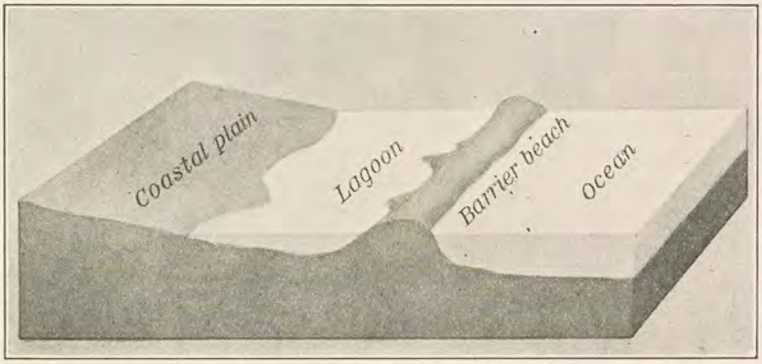

Fig. 40. Model showing development of a barrier beach and the lagoon behind it

Constructive work of ocean waves. As the waves with their tools batter down the land and incidentally acquire new tools, so during this process these tools become smaller and smaller. Angular bowlders become rounded cobbles, and these are in turn reduced to pebbles, sand, and silt. To this material is added the sediment brought in by streams from the lands.

The most important factors in the reduction of this wave-derived and stream-derived material are the shoreward shifting of the material upon the breaking of the wave and its subsequent seaward movement by the undertow. Since stones are lighter when immersed in water, they are then most easily moved. Hence, especially during storms, as is indicated by the deep sounds coming from it, this huge mill is at work upon a great thickness of sediment, reducing it to its final product, silt. This silt is held in suspension by agitated water until it gradually sinks into the quieter, deeper water far beyond the breakers.

Since quartz (SiO_2) is the most abundant and one of the hardest of the rock constituents, it naturally becomes the most abundant remnant in the process of reduction from bowlders to silt. Quartz becomes battered to the size of sand grains in a comparatively short time, but reduction in size from this point is exceedingly slow, since the particles are too small to be easily broken and too hard to become readily ground to silt. This easily moved quartz sand is then carried by waves striking the shore obliquely and by the shore currents along the shore, forming the principal part of the beach. The *beach* consists of all the loose material, from bowlders to silt, that is in the process of being ground up by the waves. Its upper margin is the level reached by storm waves at high tide. In some places at the foot of steep cliffs, beaches are entirely wanting.

Where the slope seaward from shore is very gentle the waves strike bottom some distance from shore. Along this line, where more material is brought by the waves than is carried seaward by the undertow, it is heaped up, forming a *barrier beach*, or *sand reef*, parallel to the coast. The water between this barrier and the mainland, seldom over 20 feet deep, is the *lagoon* (Fig. 40). Inshore winds, picking up dry sand, carry it inland, making the inner margin of the barrier ragged. This sand, aided by the wash from the land, gradually fills the lagoon, forming first a marsh and then dry land (Fig. 41). Barrier sand reefs inclosing lagoons are common on the Atlantic coast of North America from Maine to Texas. Such barriers, for example, inclose the lagoons of Pamlico and Albemarle sounds off the coast of North Carolina, and the lagoon west of Atlantic City, New Jersey.

When more material is brought in by shore currents than can be ground to silt and carried away, the barrier becomes broader, as at Atlantic City. When, however, less material is brought, the waves gradually eat through the barrier and the lagoon or marsh into the old land, as at Long Branch, New

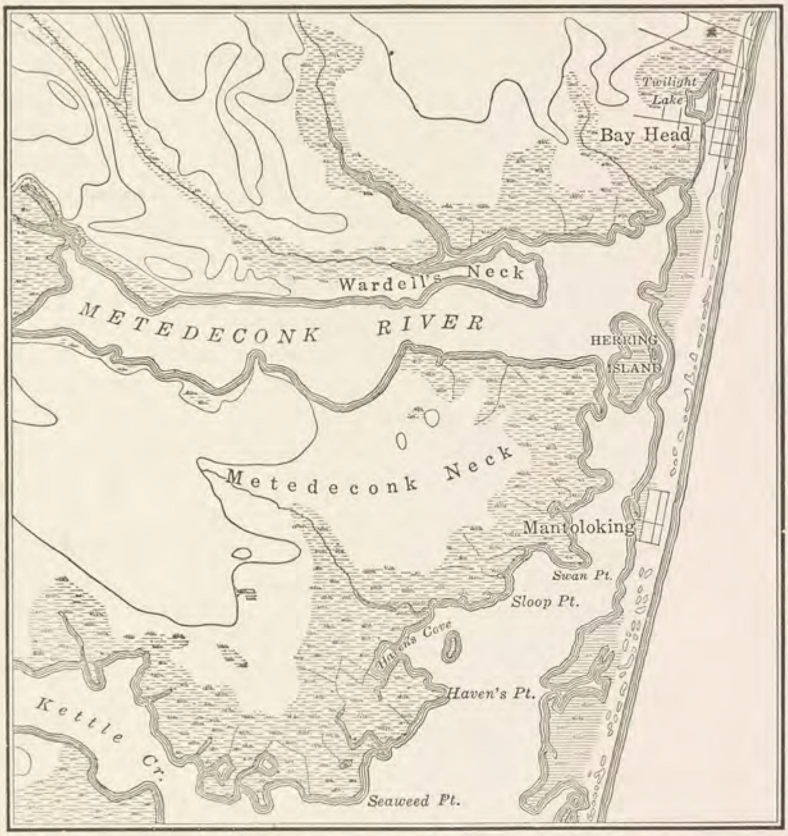

Fig. 41. Barrier beach and lagoon

The barrier beach is straight on the ocean side, due to the alongshore currents; it is ragged on the lagoon side because of the sand blown landward from the beach. Upon the beach are numerous low sand dunes. The Metedeconk River and its tributaries are drowned streams. Such submergence of the coast is characteristic of the Atlantic shores of North America and Europe. (United States Geological Survey sheet, Asbury Park. Scale: 1 inch = 1 mile; contour interval = 10 feet)

Jersey. The barrier is thus merely the necessary preliminary step in the attack of the ocean upon the land; the water must first become sufficiently deep for the waves to work.

As a rule the shore current upon a deeply indented coast line cannot enter a reëntrant but holds its course across the mouth of the bay. It follows that the current, being somewhat checked by the larger body of water that it enters, must deposit some of its sediment. If there is a sufficient amount of this sediment, the action of the waves may bring it above sea level. When this exposed deposit projects but a short distance from shore, it is called a *spit*; when it extends nearly or entirely across the bay, it is a *bar*. It is usually prevented from going entirely across by the inward and outward rush of the tide. Sandy Hook is a spit projecting from the northeast coast of New Jersey, built by the northward-moving shore currents.

The material washed from islands by the waves is carried by oblique waves or currents so as to unite island to island or to the mainland, and also to form bars or sand reefs. Such a reef ties Gibraltar to Spain. Similarly, Winthrop Beach in Boston Harbor unites two island drumlins, and Nantasket Beach unites three (Fig. 36).

DEPOSITS IN THE OCEAN

The material brought into the ocean by streams or torn by waves from the shore is distributed according to size. The heaviest material is dropped first upon entering the ocean; the lightest muds are long held in suspension and are hence carried far before gravity draws them to the bottom. There follows a succession from land seaward that may in general be divided into (1) the littoral deposits (between high and low tides, and thus forming beaches); (2) the shallow-water deposits (to the 100-fathom line); and (3) the deep-sea deposits.

Littoral deposits. Littoral deposits, consisting of bowlders, cobbles, sand, and, in protected places, mud, cover about 62,500 square miles of the earth's surface. In these deposits the ripple marks formed by the base of waves or by the forward movement of the water are exposed at low tide. At this time, also, the water returning after the breaking of the waves develops rill marks. Here live only such animals and plants as can endure a great range in humidity and temperature twice a day. A fossil example is the Oriskany sandstone (early Devonian) of the Appalachian region.

Shallow-water deposits. Shallow-water deposits, made up of sandy, muddy, and calcareous materials, cover some 10,000,000 square miles of the earth's surface. In this shallow-water zone, consisting of the borders of lands and such shallow seas within the continent as the Hudson Bay, live the vast majority of marine plants and animals. Since the penetration of sunlight to such depths is sufficient for plant growth, vegetation is abundant; and since plants abound, animals are consequently abundant. These are the great fishing grounds of the world, from which man obtains most of his sponges and pearls, oysters and fish.

In addition to the material rolled along the bottom or carried in suspension the ocean waters contain much dissolved matter brought in by streams or obtained by the ocean waters in contact with the land. From this matter in solution marine plants derive their food under the action of sunlight, and from it both plants and animals secrete skeletons for support or for protection. Some organisms, such as many plants, corals, and mollusks, make use of lime for skeletons; others, such as certain plants and sponges, use silica; while other organisms avail themselves of still other substances.

Since lime in solution is both very abundant and easily extracted, it is used by many of the lower plants and by nearly all animals. Some animals, such as those with a backbone, add phosphate to the lime; but the vast numbers of corals, crinoids, and mollusks secrete pure lime, and these animals are exceedingly abundant in the shallow seas. It follows that in areas where but few sands or muds are brought, remains of these lime supports or lime skeletons may accumulate, forming pure lime deposits of shells etc. (coquina). Numerous fossil examples are known; such are the Niagara limestone (Silurian) of New York and the Trenton limestone (Ordovician) of the Appalachian region (Fig. 122).

These skeletal remains, especially those of corals, are penetrated by vast numbers of boring animals, notably worms. The disintegration begun by the boring animals is continued by the waves, and the resultant lime mud, so conspicuous around coral reefs, is spread to great distances. To this are added huge quantities of lime mud thrown down through the action of the myriads of Drew's bacillus (a bacterium) present in these tropical waters. In this manner are formed deposits consisting of lime mud and the skeletons of many plants and animals that lived, died, and were buried in the immediate area. These deposits, upon hardening, become limestone. If the area of accumulation sinks slowly in relation to sea level, and if the organisms continue to live there, great thicknesses of limestone may form. Such deposits are known up to hundreds and even thousands of feet in thickness and from all eras.

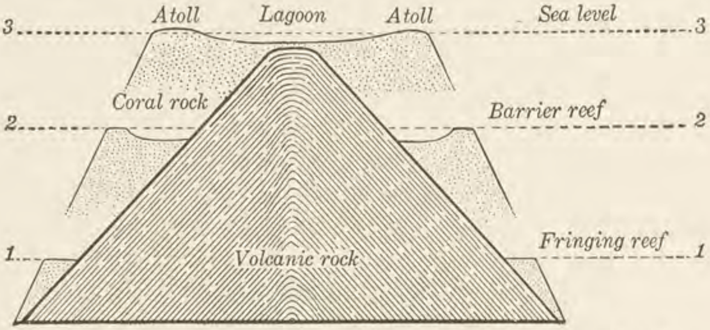

Fig. 42. Section of three stages in the history of a coral reef

Through the successive elevations of sea level (*1*, *2*, *3*) in reference to the volcanic island the fringing reef is changed to the barrier reef and this to the coral atoll. The dotted area represents coral rock

Coral reefs. There are many types of coral animals living today in the ocean, from those secreting a support of chitin with only a thin coating of lime, such as the fan coral (Gorgonia), to those secreting lime carbonate only. Of the latter, some are large solitary individuals and others are small colonial forms in which thousands of individual animals build a common support. It is representatives of such colonial forms that are responsible for the building of masses of lime up to the surface of the water, forming reefs. Reef-building corals need salt water with a temperature above 66° F. and a depth of not more than 150 feet. Coral reefs are accordingly confined to tropical seas. Many surround tropical islands and occur as fringing reefs, barrier reefs, and coral atolls (Fig. 42). The group of volcanic and coral islands east of the Philippines, known as Yap, is encircled by a barrier reef. The Great Barrier Reef off the northeastern coast of Australia has a length of 1500 miles.

Since many islands with barrier reefs have embayed shore lines and an absence of deltas, sea cliffs, and marine terraces, the usual explanation of these reefs has been that first suggested by Darwin. According to this hypothesis the typical coral reefs begin their growth by fringing the island. Subsidence of the island changes this *fringing reef* into a *barrier reef,* since the corals grow most rapidly upon the seaward side, where the waves bring to the animals plenty of food and oxygen. Further sinking results in the disappearance of the original island, leaving only a ring of reef, an *atoll,* to tell of its former presence.

A similar result would be attained, however, by a rise of the ocean level instead of the sinking of the ocean floor which supports the island. Thus, Daly in his "glacial control" hypothesis suggests for the glacial (Pleistocene) period the lowering of the ocean level in the tropics 180 feet through the combined withdrawal of water (150 feet) to form the huge ice caps of North America and Europe and the gravitative action (30 to 50 feet) of this ice. (Since the area of the ocean is 120,000,000 square miles and the Pleistocene ice sheets covered over 6,000,000 square miles of the land, with an average thickness of 3000 feet (Daly), the removal of this amount of water from the ocean would lower it 6/120 of 3000, or 150, feet.) The subsequent melting of this ice would bring about the observed rise of tropical waters. Both this phase of the Daly hypothesis and the Darwin hypothesis may be contributory to the effects noticed in coral-reef regions.

Deep-sea deposits. Deep-sea deposits, made up of very fine, land-derived muds in areas near continents, of red clay beyond these in the deepest waters, and of the oozes derived from the skeletons of microscopic animals and plants, cover 133,000,000 square miles of the earth's surface.

Oozes. Since sunlight cannot penetrate to the bottom of this great body of water, and since there can, in consequence, be no plant life at that depth, it follows that conditions of life there must be very different from those of the shallow-water zone. The surface of the ocean everywhere to a depth of efficient light penetration is a veritable meadow of microscopic one-celled plants, especially diatoms. Feeding upon the plants are vast numbers of microscopic animals, — one-celled protozoöns and the very young stages of many higher animals. This aggregation of floating forms, the *plankton,* not only forms the food of many young fish, the whalebone whale, etc. at the surface of the ocean, but is the source of all the food of deep-sea forms. Upon the death of these plankton their bodies rain down upon the sea floor beneath, where they form the food of those deep-sea animals fitted to eat them, upon which, in turn, others feed.

Many of the plankton secrete skeletons. Such plants as diatoms and such animals as the one-celled radiolarians secrete skeletons of silica. The vast majority of animals, however, which secrete a skeleton make use of lime. Upon the death of these organisms the skeletons fall to the bottom, and in the absence of other sediment, as is the case over most of the deep-sea zone, these skeletons accumulate to form comparatively pure organic deposits called oozes. When the deposit consists largely of the siliceous skeletons of the microscopic plants, the diatoms, it forms diatomaceous ooze. This is most abundant in polar waters. If it is made up largely of the skeletons of lime-secreting protozoöns, of which one of the most abundant forms is Globigerina, it is called globigerina ooze. This is most abundant in tropical and temperate zones. Upon hardening, globigerina ooze would form a chalk. (For the formation of chalk in shallow water see page 234.)

Red clay. Because carbon dioxide (CO_2) is heavy it tends to accumulate at the bottom of the ocean. Some of it is kept from doing so by the vertical currents that mix the waters, but it is still present in greater quantities in deeper than in more shallow waters. An abundance of carbon dioxide is naturally reflected in a decrease of lime-carbonate shells. In tropical regions, under the same surface conditions, deposits at a depth of less than 600 fathoms contain from 80 to 90 per cent of calcium carbonate; at 2000 fathoms, less than 60 per cent; at 2400 fathoms, about 30 per cent; and at 2600 fathoms, only 10 per cent. Accompanying the decrease in lime carbonate, oxygen unites with such organic matter as protoplasm and muscle tissue until these disappear, when it unites with the iron present, giving it the yellowish or reddish, iron-rust appearance. This sediment, the red clay, is derived not only from the residue after the solution of the organisms falling here, but also from meteorites, pumice, and volcanic and other dust carried by the higher winds. Thus a deposit of red clay is found below the 2500-fathom line. As the contour line rises above this limit the skeletons of microscopic plants and animals rapidly increase in number and in perfection of form, and soon justify the name of the deposit as an organic ooze.

Very few fossil deep-sea deposits are known: the most undoubted is on Barbados Island (p. 293).

SUMMARY OF DEPOSITION

Because of the forces at the surface of the earth (that is, the heat of the sun, gravity, and the earth's axial revolution) air and water are set in motion. These in turn cut down the lands of the earth and gradually transport them to lower-lying land areas and to the ocean. Wind (air in motion) is active in all parts of the globe, more especially in arid regions. Glaciers are local in their distribution and hence in their destructiveness. Water in its liquid phase, in rainfall, or in ocean waves is by far the most important factor. All these agents, however, aid in the disintegration of the lands and in the transportation of the débris. This débris, after its deposition, is known as *sedimentary rock,* whether consolidated or unconsolidated.

Consolidation of sediments. The change from loose sediment to solid rock is brought about partly through the great pressure of overlying sediment, partly by the heat due to this pressure, but perhaps mostly by cementation. Lime carbonate, silica, and iron are readily picked up by water and later deposited around the sand grains and mud particles as a cementing material. Deposits of lime carbonate, such as the vast accumulations due to dead shells and broken coral reefs, become hardened almost immediately through the great amount of lime cement present. If the rock becomes subjected to heat, consolidation is increased (see Metamorphism, p. 139). Hence, because of variation in the amount of consolidation, in cementing material, and in the character of the rock particles etc., sedimentary rocks, when used as building blocks, vary greatly in their ability to bear strains. Shale is the weakest and limestone the strongest. Rocks are usually weaker when placed on edge than when arranged upon their bedding planes. Wet rocks are weaker than dry ones. Sandstone when wet has about half the strength that it has when dry. A sandstone which bears a pressure of 10,300 pounds per square inch when dry collapses under a weight of 5600 pounds per square inch when wet. Of the various cementing substances silica is the strongest and most durable.

TABLE VIII. CLASSIFICATION OF SEDIMENTARY ROCKS

1. Rocks of mechanical origin
   a. Residual deposits; for example, clay from limestones
   b. Water deposits; for example, conglomerate, sandstone, clay, shale, some limestones
   c. Wind deposits; for example, sand dunes, loess
   d. Glacial deposits; for example, till
2. Rocks of chemical origin; for example, sulphates (gypsum), chlorides (rock salt), siliceous rocks (flint), ferrous rocks (iron ores), carbonates (stalactites, onyx, travertine, some limestones)
3. Rocks of organic origin; for example, phosphates, siliceous rocks (diatomaceous ooze), carbonates (globigerina ooze, chalk, shell rock, coral rock, most limestones), coal

Material eroded from the land, and removed by being rolled or carried in suspension by wind or water, forms sediment of a mechanical origin and yields such rocks as shale and sandstone. As water takes the most soluble matter from a rock a residue of less soluble and insoluble material is left behind, forming beds of sediment entirely different from the original rock. Such an erosion of limestones is apt to leave a sticky clay; of granites, a bed of sand. These are called residual deposits. Rocks of chemical origin are formed when the rock material in solution is deposited through evaporation or segregation. Similarly, rocks of organic origin result from the activity of plants and animals. (In Table VIII names of solid rocks are usually given; thus, limestone is given instead of lime mud.)

TOPICAL REVIEW

- Composition of ocean water
- Deep circulation of ocean waters
  - Massive movement
  - Movement due to increased salinity through evaporation
  - Movement due to increased density through cold
- Surface circulation of ocean waters
  - Waves
  - Ocean currents
- Effects of the movements of ocean waters
  - Destructive work of ocean waves
  - Constructive work of ocean waves
- Deposits in the ocean
  - Littoral deposits
  - Shallow-water deposits
    - Coral reefs
  - Deep-sea deposits
    - Oozes
    - Red clay
- Summary of deposition
  - Consolidation of sediments
  - Classification of sedimentary rocks

CHAPTER VIII

FORCES WITHIN THE EARTH AND THEIR EFFECTS

Since the forces at the surface of the earth tend continually to carry all land beneath the surface of the ocean, the very existence of any land is dependent upon its being uplifted from time to time. Otherwise the ocean would, in a geologically short time, cover the entire earth evenly to a depth of some 9000 feet. The cause of such uplift resides within the earth itself.

Just as the forces at the surface of the earth originate in externally derived heat, gravity, and the revolution of the earth upon its axis, so, similarly, the source of the forces within the earth is internally derived heat, gravity, and possibly the axial revolution of the earth. In the former case it is the sun's heat which is the most important factor; in the latter it is gravity and the instability of the matter within the earth.

As the forces at the surface initiate the evolution of winds, of rain, and of streams, with all their consequences, so the forces within the earth initiate the development of earthquakes and volcanoes, of mountains and plateaus, of continents and ocean basins.

Unlike our knowledge of the work of the forces at the surface of the earth, what we know of the interior and of the forces there active must be largely indirect. It must depend upon facts observed in rocks once deeply buried and now exposed at the surface through long erosion, upon the varying behavior of earthquake shocks as they travel through different portions of the earth, upon the comparative densities of various parts of the earth, upon the characteristics of the deeper rocks when poured forth upon the surface in a molten state, upon the matter which in the form of meteors comes to us from the vast spaces beyond the earth, and upon what the spectroscope tells us of matter in other celestial bodies. Facts thus obtained must be interpreted in the light of our knowledge of matter derived from field and laboratory experiments. For example, when he is looking for evidence of yielding under stress differences, the geologist's examination of the earth is like an engineer's examination of a bridge. Each is comparing the present condition with an earlier, simple, unstressed state. When the engineer sees rivet heads pressed off, surfaces scaling, and changes in microscopic structure, he is certain that the bridge has passed through a period of stress. Similarly, when the geologist finds cracks, such as joints and faults, rock beds that must have been originally horizontal but are now closely folded, and parallel arrangements of crystals as in slates and schists, he concludes that at least the outer portion of the earth has passed through periods of stress.

HEAT WITHIN THE EARTH

The deeper the earth is penetrated in wells, in mines, and in tunnels, the higher does the temperature rise. The average rate of increase is 1° F. for each 60 feet in depth, though it varies from 1° in 10 feet or less to 1° in 200 feet. Many depths of over a mile have been reached. That at least portions of the interior are very hot is shown by the liquid rock poured forth from volcanoes.

The chief sources of the heat within the earth are the radioactive elements and the pressure of outer parts of the earth upon the deeper parts.

Heat developed from the radioactive elements. The elements uranium, radium, and thorium, the most radioactive known, are more abundant in granitic rocks than in basaltic (Strutt). This indicates the greater abundance of these elements in the outer granitic zone than in the inner basaltic one. One gram of radium emits sufficient heat each hour to raise the temperature of over 100 grams of water 1° C. The amount of radioactive elements in the earth is unknown, but they must be concentrated in an outer layer of comparatively moderate thickness, for if they were uniformly distributed to a depth of more than forty miles as abundantly as they are in the surface rocks, it would follow of necessity that the earth would be growing warmer (Strutt). Throughout all stages of earth history atomic energy and contraction have probably been the principal sources of internal heat.

Heat from pressure. As a body contracts, heat is given off. In the evolution from the nebula to the dark star, as the force of gravity is constantly active through all stages of contraction, heat is being continually developed. The earth, though a dark body, is still contracting through chemical changes, a loss of water and various gases, and possibly a loss of heat. But, in addition to the heat developed by the pressure of the contracting earth through loss of water and gases, the pressure of rocks during the folding of mountains also causes heat, as does likewise, in underlying rocks, the pressure of heavy basaltic rocks poured out upon the surface.

STRUCTURE OF THE INTERIOR OF THE EARTH

Density of the earth. The contraction of the earth brings about not only an increase in heat but also an increase in the density and in the rigidity of the matter composing it. Under the powerful action of the earth's gravity all parts of the earth tend to concentrate toward the center. Matter of high specific gravity, other factors being equal, is urged toward the center more strongly than matter of a lower specific gravity. This movement would have been especially active when the earth, as seems probable, was in a molten condition, and has progressively decreased as the earth has become more solid. Since, however, gravity is continuously active, and since the moon and sun cause not only tides in the ocean but corresponding periods of greater and less pull on the solid earth mass, there follows a kind of kneading process, slight in amount but constant in operation. Whenever any movements take place within the body of the earth, and whenever any changes or stress differences occur, the heavier material probably tends to sink and the lighter to rise.

The pressure of overlying upon underlying masses of the earth rapidly increases to the center, where it is calculated at about 3,000,000 atmospheres (about 45,000,000 pounds upon each square inch). This pressure alone causes considerable increase in the density of matter. This increase of density with depth, however, is not wholly due to increasing pressure but partly, and perhaps largely, to a difference in the intrinsic nature of the materials composing the earth, — a difference proportional, in general, to the depth of the material below the surface. The specific gravity of the earth as a whole is 5.52, while the average of the surface rocks is not over 2.7. Moreover, the density of igneous rocks apparently varies according to the depth of their derivation within the earth. The average specific gravity of the igneous rocks upon the continent of North America is 2.86, while that of those from Hawaii is 3.12 and of those from Tahiti 3.20 (Iddings). These figures seem to indicate that molten rocks poured forth from the great depths of the Pacific are heavier than those of a shallower derivation.

That both density and rigidity increase with depth is likewise shown by the speed of earthquake waves. The speed is usually greatest when the earthquake originates upon the opposite side of the earth from the observer, and when the waves travel through the body of the earth; it is least when the waves travel only through superficial loose rock. Now, since the speed varies with the density of the materials traversed, it is obvious that the central portion of the earth has the greatest density. It has been determined that if a central portion of the earth, with a radius of some 3000 miles (4900 km.), had an average density of 8.5, and an outer portion, with a radius of some 900 miles (1500 km.), an average density of 3.2, it would satisfy observed facts as to the average density of the earth as a whole, the varying speeds of earthquake waves, the flattening of the earth, and the relative strength of gravity at the poles and at the equator (Fig. 3). (The intensity of gravity increases from the equator to the poles.) There would naturally be a more or less gentle gradation between the lighter outer rocks and the heavier material far within.

Zones of "fracture and flowage" and of "flowage." The action of gravity brings about an increase in heat, with an accompanying tendency to weaken molecular attraction so as to cause flowage and finally melting. Under the pressure of the walls of a large house, shale loses its rigidity and flows, and because of this is unfit for building. The same kind of rock may vary greatly in its ability to resist crushing, as is shown by the following results of experiments on rocks from different parts of Wisconsin: sandstones vary from 2000 to 17,000 pounds per square inch; limestones, from 6000 to 43,000 pounds; and granites, from 20,000 to 38,000 pounds. If other factors did not enter, this would mean that all rocks would be crushed, that is, lose rigidity, at a depth of seven miles. Experiments under high pressures have shown, however, that with increase of pressure the rigidity is raised, at least up to very high pressures; so that, according to F. D. Adams, loss of rigidity in granites occurs at a depth of about eleven miles, and in limestones, sandstones, and shales, at correspondingly lesser depths. P. W. Bridgman considers the depth for loss of rigidity in granites to be about seven miles.

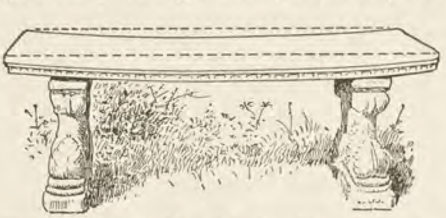

Fig. 43. A marble slab bending under its own weight

The solid line represents the present position of the stone, the dotted line the original position. Marble slabs supported at their ends have bent downward in the middle in the course of one or two centuries

Hence the superficial layer of the earth from the surface down to a depth of about ten miles is, from this point of view, called the zone of "fracture and flowage"; for from the surface, where unconsolidated mud flows, down to about ten miles, where granite and limestone similarly flow, there occur rocks that flow under the pressure there present and others that remain rigid and hence fracture under rather sudden strains. Beneath this zone of combined fracture and flowage the heat and pressure are so great that all rocks move by flowage under the application of a differential stress (Fig. 3).

It is evident, however, that time is a vital factor in determining whether the resistant rocks bend without fracturing.

A slab of marble that will break when an attempt is made to bend it suddenly will bend under its own weight in a century or two without fracturing (Fig. 43). Hence, the presence of folds at the surface of the earth, in rocks of the very hardest type, does not necessarily indicate an erosion of twelve miles of rock from above it. Instead of having arisen rapidly in the zone of flowage they may have developed very slowly in the zone of fracture.

ORIGIN OF CONTINENTS AND OCEAN BASINS

We have seen that the earth is apparently composed of an outermost layer of light siliceous rocks, the granitic zone, underlain by a heavier basaltic zone and still more deeply by heavier matter. Precise geodetic measurements show that the continents are made up of lighter matter than are the ocean basins. The specific gravity of the earth as a whole is 5.52, and of the average continental rocks 2.7, indicating that the innermost part of the earth is composed of such heavy metals as iron and nickel, — a conclusion apparently corroborated by the behavior of the earth as a huge magnet. The presence of continents and ocean basins is due to the origin and maintenance of these density differences in the outer portion of the earth. In the following paragraph is given one of the hypotheses developed to account for these facts.

The heat from radioactive elements, pressure, etc. developed near the surface is lost by conduction and radiation. In the deep-seated rocks, however, heat developed from radioactive elements would probably cause certain far-reaching changes. As the heat rises it enters a zone of lessened pressure and hence of lower fusion points, causing the liquefaction of the more easily fused rock there present. This rise would possibly be aided by the slight tidal "stress and relief" kneading process brought about by the moon and sun as the earth revolves upon its axis. In this way reservoirs of molten rock would arise. (Molten rock is not the product of simple fusion but represents mutual solution of one or more minerals.) If the heat of this molten mass became sufficiently great, it would gradually melt its way upward and into the granitic layer or even be poured out upon it. These heavy, deep-seated rocks, such as basalts, would tend to weight down the surface rocks, thus forming basins. The pressure would probably also tend to force the lighter granitic rocks away from beneath it laterally in all directions, the movement being probably caused chiefly by recrystallization, as in the movement of a glacier. The resultant depressions are the ocean basins. The granitic layer pressed laterally would aid in the elevation of the land masses, the continents. Through repetitions of such basaltic outflows the ocean basins would tend to become free from highly siliceous lavas. Today in the Pacific Ocean only basaltic lavas occur. The size of the resultant depression would depend upon the amount of basaltic lavas poured forth. With the establishment of continents and ocean basins the molten basalt would be squeezed along the horizontal planes at the junction with the lighter continental segment; up through this segment, gradually melting it, the basaltic lavas would thrust their way and would be ejected near the surface or poured out upon it. Weighing down these margins, they tend to sink and become part of the ocean basin (Barrell and Willis). Thus, during late geological times, from mid-Tertiary to the present, the greatest outflows of lava have taken place in the lands surrounding the Pacific (the "circle of fire"), in the North Atlantic (from Iceland to Great Britain), in the eastern Atlantic (from the Azores to St. Helena), in the lands bordering the old Tethys sea (from Spain to the Himalayas), in the lands bordering the Arctic (from the Yenisei River to Bering Strait), and in the islands north, including Franz Josef Land. Where the oceans were very broad, as is the Pacific, exits developed within the ocean floor, giving rise to many volcanic islands.

Isostasy. The mass of every continent, or of every mountain, tends through its gravitative attraction to deflect the plumb line toward it and thus slightly away from the true vertical. In the case of the continents, however, the actual deflection from the vertical averages only one tenth of that calculated as due to the earth relief (Hayford). This indicates that the continents stand above the ocean floors for the same reason that icebergs rise above the surface of the ocean, — because they are composed of lighter material; it is the position of equilibrium. This is corroborated by the pendulum. The time of vibration of a pendulum varies with the place where it is swung, and from the observed times are deduced the values of gravity at the various localities. It is now known through the work of half a century that the larger relief features of the earth — the continents, the ocean basins, and even the great plateaus and basins — are more or less fully in isostatic equilibrium, though unless they are locally very high there is probably not complete adjustment within areas smaller than seventy miles in diameter or of limited height or depth (Bowie).

The evidence of isostasy indicates that density differences between continents and ocean basins probably do not reach below the outer 1/50 of the earth's radius; that is, drill cores of equal diameter anywhere upon the earth, reaching to a depth of about seventy-five miles, would contain the same mass and weight but not equal volume.

Isostatic equilibrium must have been operative from early geological times, but the present relation of high and low areas on the continents is not the same as it was on the primitive earth; there has been a shifting of these zones during the sinking of geosynclines and the rise of mountains and plateaus. Such isostatic readjustments are apparently due to underflow in depth from the heavier earth segment to the lighter. From gravity observations taken near the mouths of the Mississippi, Po, Ganges, and Irrawaddy it appears that these areas are in isostatic equilibrium; that is, as the sediment is deposited upon the deltas it is apparently compensated for by a subcrustal flow toward the region of erosion.

In brief, gravity experiments have shown that the material underlying the ocean floor is much denser than that forming the continental masses. Though the material underlying high mountains is under great pressure, yet it is lighter than that forming the ocean basins. Not only are the inequalities of land surface, such as continents and ocean basins, due to the inequalities in the density of the earth, but mountain systems and large plateaus as well are due to the same cause. Isostatic equilibrium tends to exist in all oceans and on all lands, in regions of active erosion and in regions of active deposition. Thus, though the density is being constantly modified by the wearing down of one portion of the land and the upbuilding of another, the resultant inequality is apparently rectified by underground flowage, or possibly by block wedging. Such a general balancing of the various parts of the earth's outer portion upon the more deeply seated zone is called isostasy, or isostatic equilibrium.

VULCANISM

As the molten rock moves outward it may contain sufficient heat and gases to force it to the surface of the earth, giving rise to volcanoes and fissure eruptions. If too weak to reach the surface of the earth, it gradually loses its heat through conduction and hardens at variable distances beneath the surface, forming *intrusive* igneous rocks. Hence, if an extrusive flow is followed downward, as is possible in old eroded volcanic regions, it gradually merges into the intrusive type of rock.

Extrusion of molten rock. *Fissure eruptions.* As the molten rock reaches the zone of fracture it may encounter a fissure, or joint; if it has sufficient force, it widens this by pressure and wells forth upon the surface as a great lava flood. Within the memory of man only one country, Iceland, has experienced this kind of inundation. In Iceland, in 1783, lava flowed forth from a fissure 20 miles long, to a distance of 47 miles on one side and 28 miles on the other, covering an area of 220 square miles to an average depth of 100 feet.

The greatest lava outflows known throughout the history of the earth have come from such fissure eruptions. In Tertiary times 250,000 square miles at the junction of the states of Idaho, Oregon, Washington, and California were covered with sheets of very liquid lava which surrounded the hills like water and filled in the old topography in places to a depth of 4000 feet, giving to the land a monotonous, flat surface. Down through this the Snake River and its branches have cut great gashes, exposing the old land and the successive flows of lava that gradually crept up the sides of high hills and finally covered them. During very early Tertiary times 200,000 square miles in the Dekkan Plateau of India were similarly covered to a maximum depth of 10,000 feet.

These tremendous fissure flows of lava are low in silica (in other words, they are of the basaltic type), and it is partly because of this that they form such large flows. Basalt with 49 per cent of silica melts at 1250° C. and at 1300° is quite fluid, while nonbasaltic rhyolite, with 76 per cent silica, melts at 1500°, and at 1700° is still viscid (Barus and Iddings). Silica is nature's most abundant acid. It follows that the lavas that are low in silica, the subsilicic lavas, flow more readily and for a longer time than do those with a high percentage of silica, the persilicic.

Moreover, the gases cannot escape so readily from the persilicic, viscous, sticky lavas and accordingly tend to collect in large bubbles. It is from such lavas that explosive volcanoes originate. Similarly, the viscous lavas are delayed in coming to the surface, and it is probably on this account that the vast mass of this kind of molten rock gradually cools and hardens beneath the surface. This is apparently borne out by the fact that most of the great intrusive bodies, the batholiths, are high in silica.

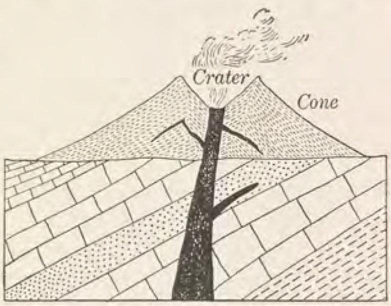

Fig. 44. Idealized section through a volcano

Lava flows, dikes, and igneous material in the conduit are in black; ash deposits seen in the cone are dotted

Volcanoes. The molten material may contain enough gases so that when the material approaches the surface and the pressure on the gases is relieved, these expand and a funnel of exit is formed at the weakest point. The typical volcano (Fig. 44) begins in some such way as this. As a bottle of soda water is charged with carbon dioxide under pressure, so the molten rock within the earth is loaded with gases under great pressure. In both cases relief of pressure is followed by escape of gases with explosive force, carrying some of the liquid with them. From the neck of a volcano this liquid lava rushes forth as a fiery spray or in larger masses, which harden while in air to volcanic ash or cinders or bombs, according to size. When, after the exhaustion of most of the gases, the lava flows forth, the remaining gases expand, filling the plastic lava with innumerable small, bubblelike cavities. Hence, after cooling, the rock has a vesicular structure.

When the explosion takes place very near the surface, where the hot lava may have encountered a considerable body of water, a broad basin, from several hundred feet to several miles wide, is formed. These basins, known as maars, abound in the Eifel district west of the Rhine in Germany. They are surrounded by a low ridge composed of only the blown-out surface rocks. The craters on the moon may have a similar origin.

If the explosion has a deeper origin, forming a deep and broad depression, the basin is called a *caldera*. Crater Lake, in Oregon, is an example (Fig. 45). The lake within the caldera has a diameter of from five to six miles and a depth of 2000 feet. A caldera of late origin is Krakatoa, an island between Java and Sumatra. In August, 1883, one half of the island was blown away, and the sea is now 1000 feet deep where the center of the mountain formerly rose.

When the supply of upward-welling energy in the form of heat, molten rock, and explosive gases is continuous and sufficient, the result is either a *continuously active volcano* or a *recurrently active* one, according to the character of the lava. Basalt is a better conductor of heat than are rocks high in silica, and accordingly it fuses at a lower temperature. Hence, if the lava is basaltic in composition, the lava in the neck is kept liquid by the easily upwelling heat aided by its gases, and can flow out as soon as enough has accumulated. The crater of Kilauea on the island of Hawaii is a typical example of a basaltic volcano. The northwest-southeast chain of the Hawaiian Islands consists of many volcanic cones rising from great ocean depths. These vary in age from the oldest at the northwest to the youngest (Hawaii) at the southeast. The chain is thus growing toward the southeast. In the southern part of this youngest island is Mauna Loa, the most active of the several volcanoes upon it, and on the southeastern flanks of Mauna Loa is the still more active crater of Kilauea. In this crater there is usually a lake of lava, boiling from the rising hot gases.

If the lava is rich in silica, its low conductivity will cause its surface in the crater of the volcano to harden over and keep on cooling downward. This will take place in the same way if the supply of new heat is slow. Such progressive solidification is accompanied by the growth of crystals. These crystals, as they grow, extrude gases from themselves and thus tend to overcharge the rest of the lava with them. (The ash of such explosive volcanoes as Pelée and Krakatoa contains many small crystals which were apparently formed in this way.) Finally

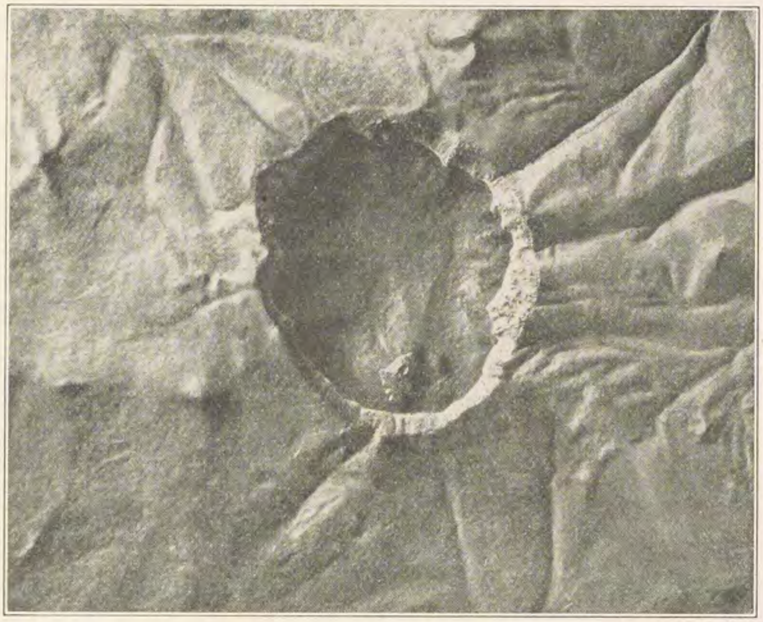

Fig. 45. Model of Crater Lake, Oregon

This caldera is four by six miles across and two thousand feet deep. After the formation of the caldera a renewal of volcanic activity produced the small cone (now an island) within it the upwelling heat becomes sufficient to melt the lower portion of the hardened plug, which is then blown out by the heavy gas pressure and is followed by another lava flow. This explains the action of recurrent explosive volcanoes like Pelée. Lavas of intermediate composition would naturally give rise to intermediate types of volcanoes. When, finally, the supply of upwelling energy ceases, the volcano becomes extinct.

Fig. 46. Earthquake belts of the Western Hemisphere today (lined zones); present and recently extinct volcanoes (dots)

The amount of fragmental material ejected by explosive volcanoes is very great. Krakatoa, in 1883, hurled forth $4\frac{1}{3}$ cubic miles, and Temboro, in 1815, ejected $28\frac{1}{2}$ cubic miles. During the eruption of Katmai at the base of the Alaska peninsula, in June, 1912, ash fell to a depth of 50 inches 30 miles away, and to a depth of 6 inches 160 miles away, while there was total darkness for 60 hours for a distance of 100 miles because of the great amount of ash in the air. The rock formed by the consolidation of ash is called volcanic tuff.

In the Katmai region there was probably injected at a depth comparatively near the surface a great mass of molten rock (a sill or possibly a batholith). The expanding gases from this hot mass caused the eruption of the volcano of Katmai and the minor explosions accompanied by the opening of numerous fissures in a valley five miles to the west. In the latter region there is a continuous escape of gases, and any water falling upon its surface must rise immediately as steam; this suggests its popular name, "Valley of Ten Thousand Smokes." No geysers can develop in such a region until the time, hundreds of years

Fig. 47. Earthquake belts of the Eastern Hemisphere today (lined zones); present and recently extinct volcanoes (dots)

hence, when the surface shall have become cooled to sufficient depth to develop a long conduit (see page 61).

The formation of several new volcanoes has been observed. The growth of one, Monte Nuovo in the Bay of Naples, was noted in 1538. For two years before that time there had been earthquakes in this region. Finally, in two days a cone 500 feet high and half a mile in diameter was built. The volcano continued active for a week but has not been active since that time.

Fig. 48. Cinder cone forming summit of Mount Vesuvius

A small cone of stiff lava has been built up over an opening in the side of the cone. In the foreground is a lava flow. (Photograph by Stose. Courtesy of the United States Geological Survey)

Mount Vesuvius, on the Bay of Naples, was supposed by the Romans to be extinct; but it again became active A.D. 79 by an explosive eruption, burying the Roman towns of Herculaneum and Pompeii, the former under 60 feet of mud and ash and the latter under from 25 to 30 feet of ash. Since that time smoke has continued to rise, but usually no lava is visible in the crater. At rare intervals, as in 1906, a lava flow occurs, but without much explosive action, since the lava is basaltic, though exceptionally rich in included gases. On the other hand, the volcano of Mont Pelée, on the island of Martinique in the West Indies, erupts a lava rich in silica; hence, when an eruption occurred, in May, 1902, it was explosive, and very hot gases filled with particles of rock rushed forth in vast fiery clouds, destroying the town of St. Pierre with its 30,000 inhabitants.

Gases from volcanoes. The most abundant gases emitted by volcanoes, excluding those developed through contact with the atmosphere and surface waters, include water (H_2O), carbon dioxide (CO_2), and sulphur dioxide (SO_2). There is no free oxygen. In the liquid lava of Kilauea, Day and Shepherd found, in 1912, nitrogen, water, carbon dioxide, carbon monoxide, and sulphur dioxide as the most abundant gases. The gases of which traces only were found included chlorine. These gases include those that are inherent in the solid rocks before fusion and those generated through the chemical reactions at

Fig. 49. Columnar structure in basalt poured forth during the Triassic, Orange, New Jersey

Photograph by J. P. Iddings. Courtesy of the United States Geological Survey the time of fusion. Within minute cavities in solid igneous rocks, both those hardened at the surface and those crystallized at great depths, are found such gases as carbon dioxide, sulphur dioxide, and marsh gas (CH_4).

Active volcanoes. There are over 400 active volcanoes, most of which are located either on the margins of continents or on islands near continents. The majority encircle the Pacific and extend through the Mediterranean east through southern Asia, along the lines of recently (Tertiary) uplifted mountains (Figs. 46, 47). The reason for this distribution seems to be that the mountain-making forces have here greatly fissured and fractured the rocks. This is corroborated by the fact that volcanic activity tends to die out in older mountains.

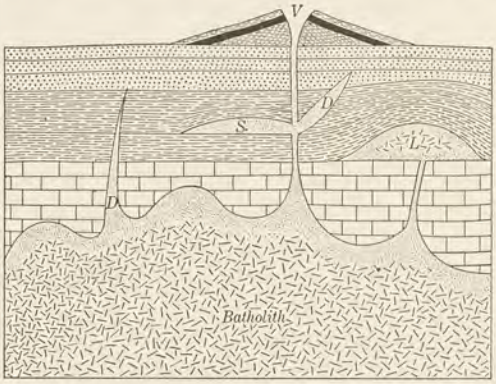

Fig. 50. Idealized section extending through a volcanic zone

The section extends through a volcano (*V*), dikes (*D*), sill (*S*), laccolith (*L*), into the upper part of the underlying batholith. It indicates also how the size of crystals depends upon the rapidity of cooling of the igneous mass. Where this molten mass comes in contact with cooler rocks solidification is rapid and hence the crystals are small, since they have only a short time for growth. Lava flows are in black. Vertical distance, 5 miles; horizontal, 10 miles

Slope of volcanic cones. Since lavas low in silica are less viscous and remain liquid at a lower temperature than do lavas with much silica, they will flow more rapidly and hence give to the volcano from which they erupt a very gentle slope, as in the Hawaiian volcanoes. The velocity of a lava flow observed on the Hawaiian Mauna Loa was fifteen miles in two hours. Volcanoes working with the more siliceous lavas will build up their cones with both ash and lava, and will as a result be much steeper; examples of such steep volcanoes are Vesuvius (Fig. 48) and Fujiyama, the sacred mountain of Japan.

Columnar structure in lavas. Since lavas at the surface of the earth lose heat and gas rapidly, they must contract. This strain is relieved with the least expenditure of energy by the radiation of three cracks from equidistant points at angles of 120°. This results in the development of a columnar structure at right angles to the cooling surface (Fig. 49).

Intrusion of molten rock. That portion of the molten rock which fails to reach the surface of the earth gradually cools underground. Such underground masses of rock have been given names which differ according to their position and size.

Fig. 51. A volcanic neck in the Mount Taylor region of New Mexico

The horizontal rocks in the foreground of the neck are undisturbed Cretaceous sediments. (Photograph by D. W. Johnson)

Dikes. When the molten material intrudes itself into a fissure and there hardens, it is called a dike (Fig. 50, *D*). Since they are formed in fissures, or cracks, dikes have great length and depth compared with their thickness. They vary from a fraction of an inch to several hundred feet in thickness and up to 100 miles or more in length. If a part reached the surface while still molten, it would give rise to the lava flows of a fissure eruption.

Sills and laccoliths. When the fluid rock insinuates itself between beds of stratified rock and there hardens, it forms a sill (Fig. 50, *S*). A dike, cutting across strata, often changes into a sill, and vice versa. Thus a sill resembles in position a surface flow which has later become covered by sediment; but, since the sill hardens under considerable pressure, it lacks the blowholes so characteristic of surface flows, and also gives evidence of having heated both the overlying and the underlying rock. When the sill is short and very thick, it is called a laccolith; it may be upward of a mile in thickness and several miles in circumference (Fig. 50, *L*).

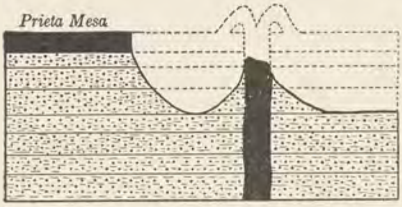

Fig. 52. A diagrammatic section of the volcanic neck and neighboring mesa shown in Fig. 51

The igneous rock is in black. The portions eroded (volcano, lava flow, upper part of neck, and strata) are shown in dotted lines

Volcanic necks. When a volcano becomes extinct, that is, when the outflow of heat at that place ceases, the lava column in the funnel hardens. After the erosion of the overlying lava flows, volcanic breccia, and surrounding rocks, the hardened lava filling the old funnel may project as a columnar mass of igneous rock,— the volcanic neck. The great diamond mines of South Africa are located in volcanic necks. Volcanic necks are abundant in the Mount Taylor region of New Mexico (Figs. 51, 52).

Batholiths. When tremendous amounts of internal heat with associated molten rock are concentrated within one area deep within the earth, they approach the surface apparently both by melting and assimilating the rocks above them and by rupturing and uplifting them. After the supply of energy ceases, the molten rock hardens, forming a batholith. Such a batholith extends downward to unknown depths, and above, where not eroded, it gives off dikes, sills, laccoliths, and usually also extinct volcanoes and associated lava flows (Fig. 50). Upon the erosion of the overlying rocks batholiths are seen to be of huge extent, surrounded by rocks which their heat and gases have metamorphosed (see page 139). Batholiths are naturally of wide extent in those parts of the earth which have been longest exposed to erosion, such as eastern Canada and New England, Scandinavia, and Finland. They also usually form the central cores of ranges of mountains. Pikes Peak, in Colorado, is a portion of such a batholith of the eastern Rocky Mountains (Fig. 53), while the Coast Range batholith of British Columbia has a length of 1100 miles and a width of from 30 to 120 miles.

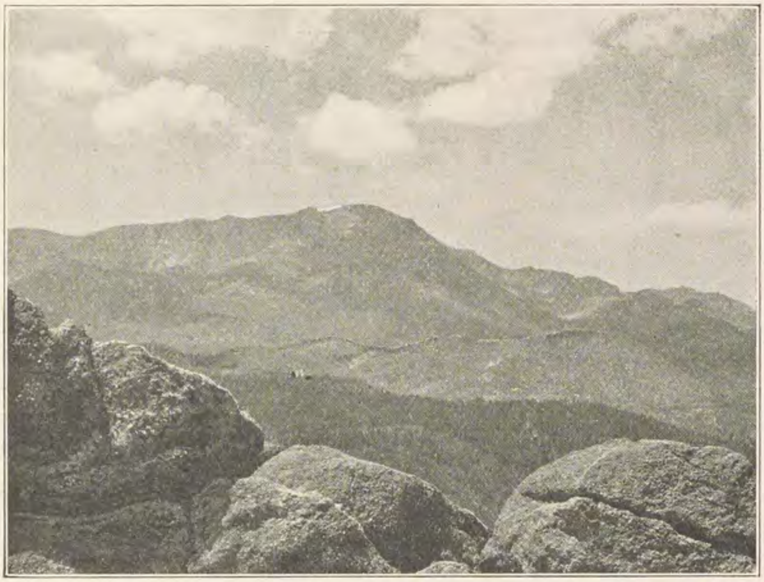

Fig. 53. Pikes Peak, seen from Mount Crest Crags, Colorado

The Peak is carved out of a granite batholith of pre-Cambrian age. (Photograph by courtesy of the United States Forest Service)

The nature of igneous rocks. Igneous rocks are formed by the solidification of molten material. The nature of igneous rocks depends upon their chemical composition and the rapidity with which they have cooled, modified by the degree of pressure to which they were subjected during the cooling process. When molten rock is poured out upon the surface, it is cooled so suddenly that the chemical substances do not have time to arrange themselves according to their affinity; it therefore cools to natural glass (obsidian) or to basalt or felsite. The deeper within the earth the cooling takes place, the slower is the process, and hence the longer is the time during which the substances in solution may arrange themselves according to chemical affinity, depending upon the degree of pressure and gas content present. The least soluble, not the least fusible, crystallize out first. The resultant growths are usually in crystal form with definite faces and angles. When cooled very slowly these crystals are large enough to be seen by the naked eye, as in granite (Fig. 54), with its many glasslike quartz grains, and in diorite and gabbro, with their burden of black, iron-bearing crystals. When cooled more rapidly the crystals are very small, as in basalts or felsites, and may be studied in thin sections under a microscope by both transmitted and polarized light. That the size of crystals depends upon

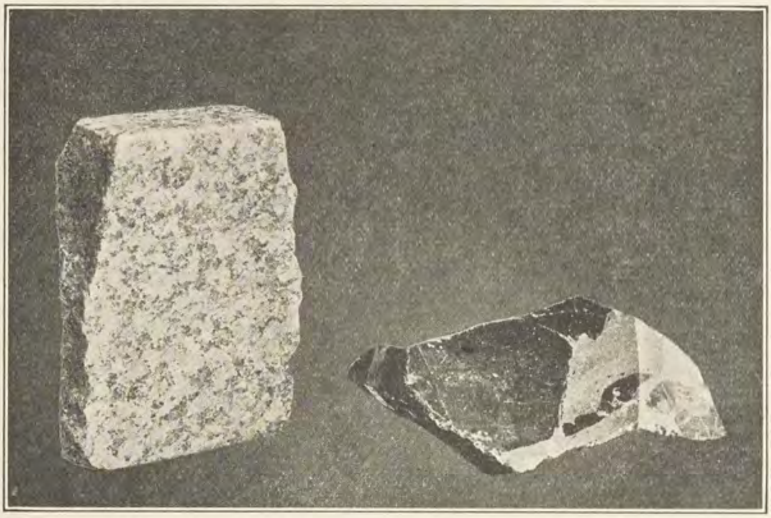

Fig. 54. Views showing texture in igneous rocks

The granite (at left) shows coarse texture; that is, large crystals, indicating very slow cooling. The obsidian, or natural glass (at right), has no crystals, indicating very rapid cooling at the surface of the earth the rapidity of cooling is well shown by the fact that it varies with the width of the dike or sill, and that the middle of wide dikes or sills contains larger crystals than the margins. The Palisades on the New Jersey shore of the Hudson River opposite New York City are a sill intruded between sandstones during the Triassic period; the middle of this sill contains larger crystals than its upper and lower margins. Iron is the principal coloring-matter of rocks. Artificial glass is colorless because it contains no iron, just as natural glass (obsidian) is dark because of its presence.

Table IX. Summary of Igneous Rocks

	According to Chemical Composition	
According to Rapidity of Cooling	*A*. Dense; crystals minute or wanting; extrusive and intrusive near surface	
	High silica rocks, usually light-colored	*Low silica rocks, usually dark to black*
	Obsidian Felsite	Basalt
	B. Coarse-grained; crystals large; intrusive at great depths	
	High silica rocks, usually light-colored	*Low silica rocks, usually dark to black*
	Granite	Diorite Gabbro

TOPICAL REVIEW

- Heat within the earth
  - Heat developed from the radioactive elements
  - Heat from pressure
- Structure of the interior of the earth
  - Density of the earth
  - Zones of "fracture and flowage" and of "flowage"

- Origin of continents and ocean basins
  - Isostasy
- Vulcanism
  - Extrusion of molten rock
    - Fissure eruptions
    - Volcanoes
    - Gases from volcanoes
    - Active volcanoes
    - Slope of volcanic cones
    - Columnar structure in lavas
  - Intrusion of molten rock
    - Dikes
    - Sills and laccoliths
    - Volcanic necks
    - Batholiths
  - The nature of igneous rocks
  - Summary of igneous rocks

CHAPTER IX

FORCES WITHIN THE EARTH AND THEIR EFFECTS (CONTINUED)

> The centre-fire heaves underneath the earth,
> And the earth changes like a human face.
>
> BROWNING

The surface of the earth is continuously changing. One land area slowly sinks, permitting the incoming of the ocean waters or the development of interior seas; in another region the land gradually rises, causing the retreat of the ocean or the development of a mountain or plateau. Such movements are, as we have seen, ascribed to isostasy. The gradual shrinkage of the earth finds expression mostly in the ocean basins. Since the oceanic segments thus sink more rapidly than do the continental, they crowd against the continents, forcing them up into higher land areas, and at the same time withdraw the ocean waters from lower-lying areas. Such periods of emergent land areas are, in turn, followed by periods characterized by widespread epicontinental seas. The dumping into the oceans of the material eroded from the higher lands gradually causes a rise of ocean level, flooding the lower-lying lands. Movements originating in the plastic parts of the earth's interior, beneath the zone of fracture, are transmitted through this brittle zone to the surface (Fig. 3). The depth of the outer layer of the earth to which cavities may exist (that is, the zone where fractures may occur) naturally varies for different rocks, but it is believed that even the most resistant rock collapses at a depth of twelve miles, and hence that no fractures can exist below this. Thus the movement which in the plastic zone is expressed in flowage is, in passing through the brittle zone, expressed in a series of jars and slips, due to the breaking of rocks under tension or, more usually, to the slipping of one rock mass past another.

CHANGES DUE TO MOVEMENT IN THE ZONE OF FRACTURE

Earthquakes. Because the superficial portion of the earth is dense, rigid, and elastic, jars or slips originating in the zone of fracture will be transmitted through it to the surface by vibration. Such vibratory, or quaking, movements of the earth are known as earthquakes.

If the slip occurs near the surface, it may express itself there as a movement of one mass of earth past another mass. The earth in the zone of fracture is made up of larger and smaller blocks, usually comprising many thousand cubic miles of rocks, which move as units past one another. These blocks are held against each other by friction until the strain becomes too great, when they slip and an earthquake results. A slipping of an earth block along a line of fracture is called a *fault* (Fig. 55), and the line of intersection of this plane with the surface of the earth is the *fault line*. A displacement, or fault, may be vertical or horizontal or both. A vertical movement took place recently in the St. Elias range, affecting especially the Yakutat Bay region which pierces it. Here, in September, 1899, one area was submerged beneath the sea, killing the forests, while another was elevated, in one region to a height of 47 feet, as was shown by the wave-cut cliff and by the barnacles and sea mussels clinging to the rocks at that height. In the San Francisco earthquake of April 18, 1906, the vertical displacement was not more than from one to three feet, while the horizontal movement, as shown by the separated ends of fences, was from eight to twenty feet. The fault line along which the movement causing this earthquake occurred was traced for a length of 600 miles. An earthquake in Japan, in 1891, was produced by a fault traced for forty miles, along which the western side

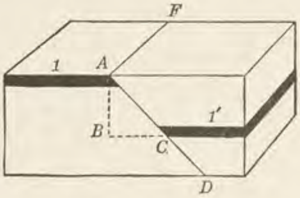

Fig. 55. A fault

AD, fault line in depth along which the coal bed *1′* has slipped from its continuation with *1*; *AF*, fault line at surface of the earth; *AC*, length of slip; *AB*, the throw, or vertical separation of *1* and *1′*

sank from two to twenty feet and the eastern side was moved northward thirteen feet. The vertical displacement is at times very great. Off the coast of Greece, in 1873, the telegraph cable broke during an earthquake. The break was located seven miles from shore, where the water was found to be 2000 feet deep instead of 1400 feet, as it had been before. In 1885, also near Greece, the repairing vessel found a difference of 1500 feet between bow and stern soundings.

Distribution of earthquakes and their causes. Since earthquakes are due to jars from the breaking of rocks within the earth or to slips brought about through the readjustment of masses of rock to strain, they should naturally be looked for where forces within the earth are now elevating mountains or have recently shoved them up, and hence where the average slope of the ground is the greatest. Thus it is not strange that, of the 4000 earthquakes which keep the surface of the earth in vibration every year, 52 per cent occur in the Mediterranean belt (from Spain and Algeria through the Caucasus and Himalayas to eastern China and the East Indies), 41 per cent in the Pacific belt (the western coasts of the Americas, the Aleutian Islands, and the islands off the eastern coast of Asia and south through New Zealand), and only 7 per cent in the rest of the world (Figs. 46, 47). The mountains of the Mediterranean and Pacific belts were uplifted very recently in geologic time, — during the late Tertiary; in places these mountains are still growing, and are thus of steep gradient. The average slope from the northeast coast of the main island of Japan to the Tuscarora Deep is one in thirty. Earthquakes are stronger and more frequent on the outer, seaward slope of Japan than on the inner, landward slope. Throughout these regions readjustments of earth blocks are continually in progress. The Japanese earthquake of September, 1923, which laid waste the cities of Yokohama and Tokyo, was due to such a readjustment. According to Jaggar the mass uplift of this entire region, accompanied with many downfaultings, was apparently due to igneous intrusion in depth. It is, moreover, in such regions of readjusting earth blocks that molten rock finds easy access to the surface, through the formation of volcanoes. During the ascension of this lava its pressure causes the sudden breaking and displacement of rocks, and thus, for this additional reason, earthquakes occur in such regions.

The earthquake shocks in the rest of the earth are due to various causes. The Charleston (South Carolina) earthquake of August 31, 1886, was doubtless due to the slipping of an earth block, as are those numerous earthquakes which occur along the fault line which runs from Iceland to the Azores and south. The Kingston (Jamaica) earthquake of January 14, 1907, was probably caused by a slump of the delta upon which the town is situated. The series of earthquakes which devastated the lower Mississippi River Valley in 1811 was probably due chiefly to the great weight of sediment laid down in that region by the Mississippi in recent geological times, causing a readjustment of the earth blocks beneath. This produced the most violent earthquake known in North America. Upward of two thousand shocks, eight of which were severe, extended over a period of three months, from December 16, 1811, to March 16, 1812. Boundary lines were so confused that the government had to resurvey 1,000,000 acres, while many depressions were formed, one of which, Reelfoot Lake, in northwestern Tennessee, has an area of 5 by 25 miles, its recent origin being shown by the dead trees still present within it.

Destructiveness of earthquakes. Scarcely a day passes when the earthquake laboratories distributed throughout the world fail to record one or more earthquakes. The earthquake-recording instrument, the seismograph, is extremely delicate. Seldom, however, is an earthquake of sufficient strength to cause the fall of buildings or the formation of large ocean waves, the principal causes of the destruction of human life. The jar causing the earthquake is transmitted as a vibration through the elastic earth to the surface, where objects, not held in place by the pressure of overlying rocks, are projected into the air, just as the tap of a hammer on the under side of a marble table will throw into the air a glass ball resting upon its surface. In other words, the vibratory movement within the earth is converted into the mass movement of objects upon its surface (Fig. 56). Hence buildings are shattered by the earthquake shock, and gravity causes their collapse and the resultant loss of life. In 1812, in Caracas, Venezuela, 10,000 persons were killed, and on December 28, 1908, 200,000 perished in the destruction of the cities of Messina and Reggio. These two cities, situated on the narrow strait separating Sicily from the mainland of Italy, are in a region where readjustments of the earth blocks are almost continually taking place, consequently giving rise to numerous earthquakes.

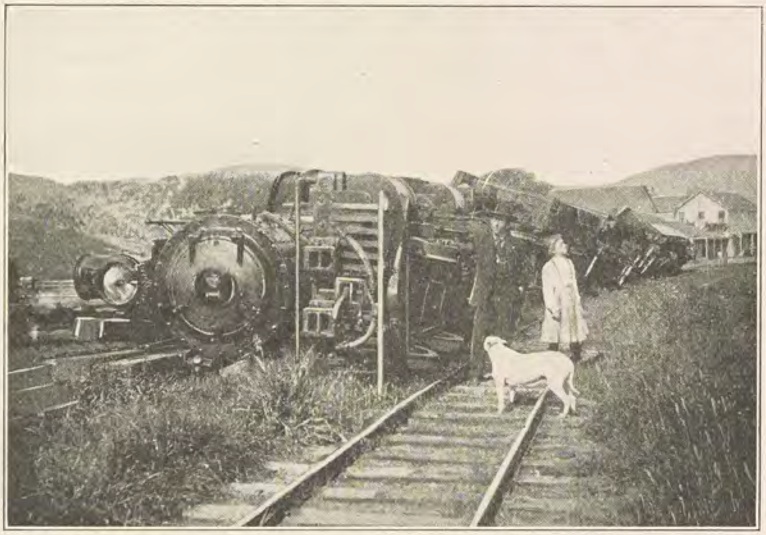

Fig. 56. Train overturned by the earthquake of April 18, 1906, Marin County, California

The earth movement was horizontal. (Photograph by Gilbert. Courtesy of the United States Geological Survey)

When a severe earthquake shock strikes the border of the ocean, it may thrust the water away from the shore. Upon the return of this water a breakerlike wave develops as it strikes the sloping shore, and rushes over the neighboring lands. A submarine shock may produce a similar wave. In the Lisbon earthquake of 1755, after the first shock the sea retreated from the harbor, but returned in a wave 60 feet high and completed the destruction of the city, causing the death of 30,000 persons.

The most destructive of all known earthquakes was the Japanese earthquake of September 1, 1923, which completely destroyed the city of Yokohama and much of Tokyo, as well as the surrounding region. The combination of the fall of buildings and the consequent fires, together with the great sea wave, resulted in the death of 400,000 persons and a property loss of $5,000,000,000.

The distance each rock particle within the earth is moved, that is, its elastic rebound, or amplitude of vibration, is very slight. A movement of five millimeters within the earth will shatter a chimney at its surface; a shock of twenty millimeters will destroy a city. It is the suddenness of the shock which makes it effective. The shocks move through the earth at a rate of about 375 miles per minute, indicating a rigidity greater than steel; they travel much more slowly through the surface rocks, as has been shown with gunpowder,—through slate at 1088 feet a second and through loose sand at 825 feet a second. Through water the vibrations move still more slowly. In 1896 a great sea wave killed 27,000 persons in Japan. It was eight feet high when it reached Honolulu; as registered by tidal gauges it had an average speed of 681 feet per second in Honolulu and of 664 feet per second at San Francisco.

The breaking and grinding of the rock thrown into vibration, accompanied by the falling and breaking of objects upon the surface of the earth, gives rise to a rumbling roar immediately preceding and accompanying the earthquake shock.

Joints. The sinking or rising of a land mass produces tension, often tortion, in the surface rocks. The necessary result of this is the production of more or less vertical and parallel cracks or joints; such jointing is doubtless hastened by the passage of earthquake waves through these tensed rocks. That the formation of joints is sudden is evidenced by those occurring in conglomerates where the joints, instead of going around, pass *through* rounded pebbles. Joints may extend horizontally many hundreds of feet; vertically they gradually disappear, as they cannot extend below the zone of fracture. They are usually confined to a single rock mass, and are seldom equally spaced for long distances. Since, throughout the vicissitudes of earth history, the rocks have become tensed in various directions, many series of parallel joints have resulted. Joints are thus an aid to quarrying (Fig. 64), and, since they form a line of weakness, they at times control the direction of streams and the formation of coves at the margin of a lake or ocean.

Faults. When surface rocks are drawn downward or pushed outward by earth stresses, a slipping of one earth block or a set of earth blocks past another set usually takes place along joint planes either already in existence or produced under the present tension. Such slipping, or faulting, because of the great pressure involved, is apt to give a slickensided, that is, a polished, surface to the zones of slipping. Seldom is a large displacement confined to a single plane (p. 122 and Fig. 61).

In the production of very steep slopes and vertical cliffs, of graben-like valleys and of block mountains, joints and faults are vital factors in giving a variety to the earth's scenery.

CHANGES DUE PRIMARILY TO MOVEMENT IN THE ZONE OF FLOWAGE

Development of Mountains and Plateaus

Contraction of the earth. The many folded mountains upon the surface of the earth, found from pole to pole and upon all continents, give evidence (1) that the earth within is contracting or (2) that the material of the surface is at intervals expanded or (3) that continents at times slide, with consequent crumpling, over an underlying plastic zone. The first hypothesis appears to be supported by the majority of facts. Contraction of the earth may occur through loss of heat from its original molten state, through the molecular rearrangement of substances within, which tends toward reduction in size, and through the loss of water and gases through vulcanism and of such elements as helium from radioactive matter.

Folds. When the two parallel edges of a sheet of paper laid upon a table are moved toward each other, the sheet bends upward into a fold. Similarly, when strata are slightly and gently shortened, they bend into folds. A simple fold which bends upward is called an anticline (Fig. 57); when it bends downward it is known as a syncline (Fig. 58). Cross sections of any large mountain show it to be composed of many anticlines and synclines.

Fig. 57. A small anticline in slate

Note the thinning of the laminæ on the limbs (sides) of the anticline, where occurred the greatest pressure producing the fold. (Specimen one foot high)

Folded mountains. *Geosynclines* (Fig. 59). Elongate and comparatively narrow areas of depression, such as the valleys of central California and of the Po River, occur both within continents and upon their borders. They are great depressions in the surface of the earth and are hence called geosynclines or "earth troughs." Such depressions within the confines of a continent or upon its edges are very apt to receive notable accumulations of sediment. The combined plain of the Indus and Ganges rivers represents such an accumulation, derived mainly from the Himalaya Mountains to the north. This Indo-Gangetic geosyncline came into existence with the upbowing of the Himalaya range in mid-Tertiary times; since that time the mass of sediment constantly poured into this downsinking trough has, except at rare intervals, been a barrier of sufficient height to exclude the ocean.

The geosyncline represented by the shallow seas extending along the eastern coast of Asia from Kamchatka to Siam, and separated by islands from the deep Pacific, receives much sediment, especially in that portion known as the Yellow Sea. So likewise the depression occupied by the North Sea receives most of the sediment eroded from central and northern Europe.

The sedimentary rocks of the Appalachian Mountains give evidence that they were deposited in a geosyncline (Fig. 101). Considering only those in age from upper Cambrian to Pennsylvanian inclusive, the sediments now folded into the Appalachian range have a thickness of about 25,000 feet in eastern Tennessee, decreasing, away from the source of the sediments, to a thickness of 5000 feet in Iowa, far west of the geosyncline. The sedimentary rocks which make up the Alps were likewise deposited in a geosyncline to a thickness of 50,000 feet, decreasing rapidly away from the zone of maximum thickness.

Fig. 58. A syncline and an anticline developed in Triassic rocks, Cook's Inlet, Alaska

Photograph by T. W. Stanton. Courtesy of the United States Geological Survey

Origin of geosynclines. Depressed tracts upon the continents are elongated parallel to the nearest coast line. The great deeps of the ocean basins likewise clearly tend to be elongated in a direction parallel to the nearest coasts. Continents and ocean basins are in this respect subject to the same law, but nowhere in the ocean basins is there evidence of mountain-folding after the manner of the Appalachians or the Alps.

Such sinking upon the land or at the borders of the sea tends to be counterbalanced in a neighboring area; if one area is depressed, another near it is bowed up (see Fig. 59). An initial cause of such sinking may be a gentle flexure of the surface of the earth at this place, brought about through lateral pressure from a neighboring ocean basin. Such downbending is usually accompanied by a bordering upflexure, just as upon a bent sleeve a fold borders a depression.

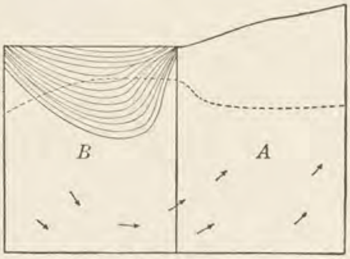

Fig. 59. Ideal section through a geosyncline and bordering area

A and *B* represent two earth columns, each two hundred miles wide, extending from the surface to a depth of seventy-five miles. The surface of *A* is a region of erosion; that of *B*, the geosyncline, is a basin of deposition. The direction of stress movements in *B* and *A* is indicated by arrows. Note the steeper dip of the geosyncline next the old land and the rise of the curve of equal plasticity (dotted line) at the junction of the two columns

As the elevated area bordering the downflexed geosyncline is eroded the lessened pressure upon the underlying portions brings about an expansion of the elastic earth column and its consequent rise and decrease in density. This upward movement of the land is further accentuated by the chemical change toward increase in volume initiated by the relief of pressure. At the same time the deposition of the eroded material within the geosyncline will increase the pressure on the earth column beneath it, with a consequent increase in the density of the matter and hence a sinking of the surface of the earth at this point. That isostatic equilibrium may be maintained, as it appears to be in all such regions today, there must be an accompanying flow in depth from the deposition zone (geosyncline) to the area of erosion. Thus the downsinking of the geosyncline, once initiated, would tend to continue. Some such cause, or combination of causes, gives rise to the geosyncline, the necessary antecedent of folded mountains (Fig. 59).

Cause of the folding of the sediments within a geosyncline. While the geosyncline is becoming deeper and deeper the earth as a whole is contracting through loss of water and gases and from other causes. A part of this contraction is probably expressed in the rise of the eroded areas and the deepening of the geosynclinal troughs, but in time it evidently becomes easier to fold the increased thickness of sediments than to continue the depression of the trough and the rise of eroded land areas. Consequently these sediments become thrown into folds, for sedimentary rocks are, as a rule, more easily folded than are crystalline rocks, both because the individual grains are held in place less firmly and because their included water makes them become plastic at a lower temperature. It is well known that hydrous fusion takes place at a lower temperature than does dry fusion.

Location of most intense folding. Another zone of weakness would exist at the junction of the rising area of erosion and the more and more depressed geosyncline, for such non-uniform pressure as exists at the junction of these two columns (*A* and *B* in Fig. 59) lowers the melting-point and raises the solubility many times more than does uniform pressure. Hence, when the rigidity of a deep geosyncline is finally overcome by the stresses arising from the contraction of the earth, the sediments in the geosyncline are thrown into folds. These folds will be steepest near the old land which suffered greatest erosion, because there the rocks would be weak through non-uniform pressure, and the depression of the trough would be greatest; from this point the folds would become gentler and gentler until they died out upon the opposite side. This would follow, whatever the direction of the force giving rise to the folding,— whether transmitted through the area of erosion, as it apparently was in the folding of the Appalachian Mountains, or through the geosyncline, as in the Coast Ranges of North America.

Size of geosynclines and of the consequent mountains: 1. *Length.* A geosyncline may vary in length from 50 to 1000 miles or more. Its length is the length of the future mountain system, for, because of the decreasing depth of the geosyncline at its ends, the consequent ranges must likewise disappear here.

2. *Breadth.* A geosyncline may vary in width up to 250 miles or more. The width of the mountain range will depend upon the width of the geosyncline and the amount of compression it suffers in the mountain-building process. The horizontal thrust will first close all cavities and compact and thicken the beds, then bend and even fault them (Figs. 57, 58). The amount of shortening of the surface of the earth from the folding of the sediments within a geosyncline may reach 50 or even 75 per cent. According to McConnell some of the ranges of the Rocky Mountains in British Columbia were shortened from an original 50 miles to 25 miles. The geosyncline from which the Appalachian Mountains were folded was shortened 46 miles (Claypole), that of the Alps, from 300 to 650 miles (Heim), that of the Coast Range of California, 10 miles (LeConte).

3. *Height.* The height of folded mountains depends upon the depth of the geosyncline, the amount of compression during folding, the rapidity of upheaval, and, most important of all conditions, the amount of uplift due not to folding but to intrusion of material at greater depths.

Rate of uplift slow. That the upheaval of mountains is a sufficiently slow process to permit enormous erosion is shown by the streams that drained the surface of the geosyncline between the time of its emergence from the sea and its elevation into mountains. The upward movement of the land into mountains is slow enough to enable the largest streams to cut through it as fast as it is raised, as a saw cuts through the log pressed against it. Thus the Sutlej River has maintained its westward course from Tibet across the rising Himalaya Mountains to the plains of India. Though the upheaval of mountains is a slow process, it is still sufficiently rapid to deflect all except the largest streams, for observation shows that a mountain ridge is the usual divide of stream basins.

Flowage by recrystallization. Physical chemistry shows that heat increases molecular activity, increases solution, both liquid and solid, and hence increases recrystallization. It is well known that at a temperature close to fusion a crystalline substance yields slowly to stresses by recrystallization. The process is physically somewhat similar to the flow of a glacier. At the minute points where pressure and consequent heat are greatest, fusion occurs. The molten particles flow to the points of least pressure and there again crystallize. The flow should therefore be fastest when the average temperature of a rock is near the fusion point. Near the surface especially, time is probably the factor which determines whether a rock will flow or fracture (Fig. 43).

Plateaus. Not only are the surface rocks within the geosyncline folded, but the entire surface of the geosyncline and of the eroded lands as well is elevated by the thickening of the earth column beneath it, through crushing, heating, and the inflow of matter, either liquid, or solid through recrystallization. The folding of the Himalaya Mountains in mid-Tertiary times was accompanied by the broad uplift of the plateau of Tibet.

Apparently, when the downsinking of the ocean basin finds no thick geosynclinal deposits to relieve the consequent pressure upon its sides, the uplift is entirely of a plateau character. Thus, the Appalachian geosyncline was folded at the close of the Paleozoic, was reduced to a peneplain during the Mesozoic, and during the Tertiary was raised 2000 feet without folding, — a plateau uplift. Such uplift, unaccompanied by folding, though frequently with block faulting, occurred during the Tertiary throughout western North and South America, usually between the Rockies and Andes on the east and other mountain ranges on the west. Such an intermontane plateau in North America is the combined high plateaus of Utah and the Great Basin of Utah and Nevada, which has a width of 500 miles and an average height of 8000 and 6000 feet respectively. In South America the plateau of Bolivia has a maximum width of some 300 miles and a height of from 12,000 to 13,000 feet. It is thus seen that plateau-forming movements are much more massive than mountain-forming ones and are next in magnitude to the movements which form continents. They are due to more deeply seated thrusts than are folded mountains. Plateaus are smaller platforms upon the larger continental platforms.

Mountains due to faulting. *Block mountains.* The inflow of matter underneath may at times arch the region of erosion, thus causing tension in the outer zone of fracture, with a consequent settling (that is, faulting) of larger and smaller earth blocks, giving rise to block mountains. Such is the origin of the Great Basin of Nevada and western Utah, which consists of north-and-south-trending blocks between the Wasatch Mountains on the east and the Sierra Nevada on the west; these blocks average a hundred miles in length and thirty miles in width (Fig. 101). The presence of lava flows and of mineral deposits requiring for their formation hot intrusive rocks gives evidence that this old land was invaded in depth during the Tertiary by molten rocks,— the cause, or an accompanying cause, of the tension of the surface rocks. The movement of these mountain blocks continued throughout the Tertiary to the present.

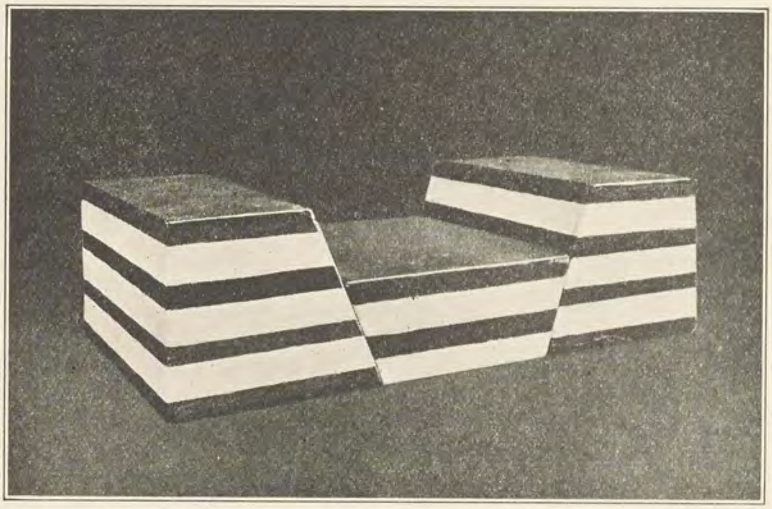

Fig. 60. Model of a graben

The central block has slipped downward

Grabens (Fig. 60). When the downfaulted portion of the earth's surface is comparatively narrow, it is called a graben. The mountains of the Vosges and Black Forest are the edges of earth blocks exposed through the sinking of the intermediate blocks. The downsunken portion is twenty miles wide and extends from Mainz, Germany, to south of Basle in Switzerland. This downfaulted zone is known as the Rhine Graben. The dip of the rocks on either side indicates that the region was arched before the keystone was downfaulted (Fig. 61).

The longest succession of grabens known is the gigantic rift valley of Africa, extending from Lake Nyasa in southeastern Africa north through lakes Tanganyika, Albert, and Rudolf, the Red Sea, and the Jordan Valley; a shorter graben runs south from Lake Rudolf through Lake Baringo. Throughout the length of this series of long, narrow depressions are many salt lakes, some completely dried up, usually with high, rocky walls. The entire length is dotted with now hardened lava flows, which in some places conceal the graben and in others merely line the cliffs, as along the shores of the Red Sea. The downfaulting occurred during the late Cenozoic (Gregory). In Palestine the graben has a width of from five to nine miles and a length of over three hundred miles, extending from Mount Lebanon on the north to the Red Sea on the south. This narrow, depressed zone is now partially occupied by the Sea of Galilee, the Jordan River, the Dead Sea, and the waters of the Red Sea in the Gulf of Akaba. Hardened basaltic lava flows are numerous, especially in the region of the Sea of Galilee. The earth block on the west of the graben, known as the tableland of Judea, is 2000 feet above sea level; to the east are two blocks,—the tablelands of Moab (3000 feet) and Edom (4000 feet). This Moab-Edom plateau merges eastward with the Syrian and Arabian deserts. The lowest point in the Dead Sea is 2570 feet below the level of the Mediterranean Sea (its surface is 1300 feet below that level), showing that the

Fig. 61. Vertical cross section through the Rhine Valley, which shows the Rhine Graben

a-b represents the present surface of the land, the strata above having been removed by erosion since the development of the graben in the mid-Tertiary. (Modified from Schmidt) graben has sunk over 4500 feet past the western block and from 1000 to 2000 feet more past the eastern blocks (Russell).

Mountains due to erosion. After folding, uplift, and tilting have produced broad folds, plateaus, and block mountains, the work of wind and water is needed to produce mountains as we know them today. Erosion, beginning with the initial rise of the mountain area, continues without interruption until the uplifted areas are worn down below sea level and below the reach of storm waves, but during this process of leveling occur the various stages of mountains known to us.

A very young stage of dissection of folded mountains is seen in the Jura Mountains of northwestern Switzerland. Here the valleys are dominantly the downfolds (the synclines), and the mountain ranges are the upfolds (the anticlines).

In time, perhaps largely because the streams in the synclines have their energy consumed in carrying the sediment brought to them by their tributaries, and possibly because the crests of the anticlines may be more stretched and hence weaker than the base of the synclines, the tributaries develop valleys along the tops of the anticlines. The valleys in such cases lie in the softer rocks, the harder rocks standing out as mountain ranges. This is the young stage of erosion reached by the majority of existing mountains, such as the Rockies, Andes, Alps, Caucasus, and Himalayas. In such ranges there may be individual peaks left by the erosion of the rocks about them, as Mount Everest in the Himalayas and Pikes Peak of the eastern Rockies (Fig. 53).

An older stage of erosion is seen in the Green Mountains, the White Mountains, and the Appalachians. Southern New England and all northeastern Canada, which formerly had lofty mountains with a general north-south trend, are old; here only the roots are preserved.

At any stage of erosion a mountain may be elevated anew. Nearly all mountains have had such stages of reëlevation. The Appalachians represent mountains that had at one stage been worn down to a peneplain before reëlevation. Of this the even sky line, formed by the uniform heights of the higher ranges, and the entrenched meanders are evidence, while the parallel arrangement of the mountain ranges indicates that the valleys have been carved out of softer rocks and that the ranges are the projecting edges of the harder rocks exposed because of the original folding of the mountains (Figs. 14, 91).

There are thus in folded mountains three periods: the pre-orogenic, or the time of the development of the geosyncline and its filling with sediment; the orogenic, or the time when these sediments are folded and uplifted; and the post-orogenic, or the time of their erosion into the well-known types of scenery.

When a stream cuts deeply enough into horizontal rocks, mountains naturally result. An early stage of this type is seen in the mile-deep gorge of the Colorado Canyon in Arizona. A later stage appears in the Helderberg Mountains and the Catskill Mountains in eastern New York; these represent the edges of horizontal strata exposed by the Mohawk and Hudson rivers.

Mountains due to igneous agencies. *The extrusion of lava and ash.* The lava and ash expelled from a volcano frequently build up very high mountains. The Hawaiian Islands are the tops of such mountains rising from the floor of the Pacific Ocean to a height of 30,000 feet. Another example is Fujiyama (Mount Fuji), which rises to a height of 12,400 feet from the level of the sea.

The intrusion of lava. At times the molten material injected from below arches the rocks above it to mountain heights. The Henry Mountains in southern Utah have been thus raised through the injection of a score of laccoliths.

Summary example (Appalachian Mountains). The rocks composing the present Appalachian Mountains are made up of layer upon layer of such sediments as sandstone, limestone, and shale. These indicate by the fossils inclosed in them, by the frequent mud cracks, cross bedding, and coal beds, and by the coarseness and color of the sediment that they were laid down during an alternation of fresh-water and marine conditions, with the increasing dominance of the former in the upper (later) beds. These strata, deposited from the beginning to the close of the Paleozoic, as indicated by their fossils, continue westward to beyond the Mississippi River, growing ever finer and thinner and more calcareous. In eastern Tennessee 25,000 feet of sediment was deposited, consisting largely of sandstones and shales, while in Iowa there is a thickness of 5000 feet, nearly all of which is limestones and calcareous shales. The greatest thicknesses of sediment occur in the eastern portion, within an area some 200 miles in width from east to west. This great depositing trough is called the Appalachian geosyncline. Since the greatest thickness of sediment, consisting mostly of sandstone and shale, lies to the east, while westward the sediment becomes much thinner and more calcareous, it is concluded that the land from which the sediment was eroded lay to the east. The western margin of this now vanished land (Appalachia) includes New England and the strip to the south of it, east of the Appalachian Mountains. To the westward of the geosyncline extended the interior ocean of North America, shallow, as is indicated by the remains of life that dwelt in it, probably never over 600 feet in depth, and frequently and for extended periods replaced by dry land.

Thus, throughout millions of years, as the trough to the west (Appalachian geosyncline) sank, receiving layer upon layer of sediment, the continent of Appalachia to the east rose, furnishing new rock for erosion. At times the trough became dry land, and flood-plain deposits or even alluvial fans took the place of marine beds. Finally the sediment-filled trough yielded to the lateral pressure exerted by the contracting earth and was thrown into folds. The greatest folding occurred at the junction of the geosyncline with the old land, where the depression of the trough was deepest, with consequent maximum flexure; hence this was the region of maximum difference of pressure within the rocks. From this line of maximum folding (the igneous and other crystalline rocks of the Blue Ridge of North Carolina and northward) the folds decrease in height and in intensity of metamorphism westward. In eastern Pennsylvania the closer folds of the rock are accompanied by anthracite coal, while as the folds flatten out, in western Pennsylvania, the coal becomes the nonmetamorphic bituminous, and so continues throughout the flat-lying beds to its point of disappearance west of the Mississippi River.

METAMORPHISM

Great pressure or heat, acting usually through water and gases, induces changes in the mineral content and in the arrangement of the minerals in the rocks so affected. Old characters are replaced by new. New minerals are formed, but the rock is not melted. This is true whether the rock is of sedimentary or of igneous origin. Rocks so changed are called metamorphic rocks, and the process of change is metamorphism.

Fig. 62. View showing cleavage in slate, Bangor, Pennsylvania

The mud now forming this slate was laid down in the ocean during the Ordovician and metamorphosed into slate during the folding of the Appalachian Mountains in the Permian

Contact metamorphism. When a dike or other body of molten material is intruded into a cooler rock, the heat affects the cooler rock to a distance varying from a few inches to many feet, depending upon the amount of heat, water, and gases present.

In the Cerrillos coal field of Cretaceous age in New Mexico, two thick intrusive sheets of igneous rock yielded sufficient heat to change many thousand tons of bituminous coal into excellent anthracite. Near Raton, New Mexico, the intrusion of several sills above, below, and within a bituminous coal bed of Cretaceous age has changed the coal to a true graphite which is sufficiently pure to be used for paint; and at a distance of only four miles from the graphite mine the unmetamorphosed bed is being mined for bituminous coal (Lee).

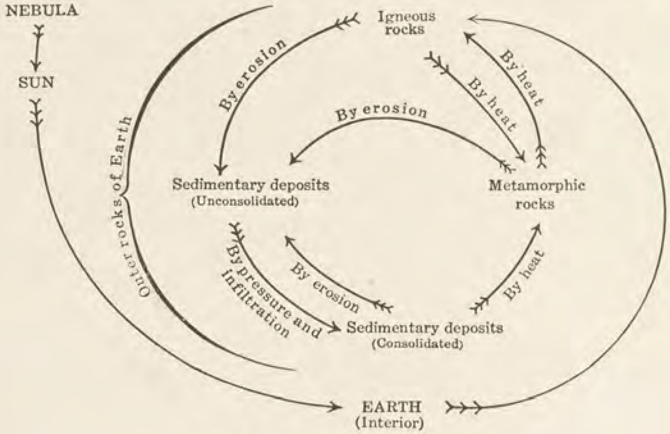

Fig. 63. The cycle of rocks

The intrusion of a widespread batholith will metamorphose rocks over a large territory, but always, in contact metamorphism, the principal agency is the heat of the igneous rock.

Regional metamorphism. Usually the most widespread metamorphism is due to the heat developed in the folding of mountains. Where mountain-folding is most intense, there the rocks have suffered a maximum of metamorphism. Thus, aside from igneous intrusions, the rocks in the center of mountain ranges consist of schists, slates, quartzites, and marbles. In passing from the center of the Appalachian Mountains, as from eastern Pennsylvania to the western part of the state, the sedimentary rocks change from schists, slates, quartzites, and anthracite coal to shales, sandstones, and bituminous coal.

Cleavage in slate. Cleavage in slate is developed at right angles to the direction of pressure through a shortening or lengthening of the minerals to fit their Procrustean bed. It is due (1) to the flattening, that is, the lengthening, of particles in this direction, and (2) to the fact that new minerals similarly grow with their long axes in this direction; that is, their growth takes place more readily along lines of least resistance. Thus from the direction of cleavage we determine the direction of the mountain-making forces (Fig. 62).

TABLE X. SUMMARY OF METAMORPHIC ROCKS

SEDIMENTARY ROCKS			
LOOSE	COMPACTED	METAMORPHIC	
		Moderately	*Intensely*
Gravel	Conglomerate	Gneiss	Schist
Sand	Sandstone	Quartzite	Schist
Silt and clay	Shale	Slate	Schist
Lime deposits	Limestone	Fine-grained marble	Coarsely crystalline marble

IGNEOUS ROCKS		
NORMAL	METAMORPHIC	
	Moderately	*Intensely*
Fine-grained rock	Fine-grained gneiss	Schist
Coarse-grained rock (granite etc.)	Coarse-grained gneiss	Schist

TOPICAL REVIEW

- Changes due to movement in the zone of fracture
  - Earthquakes
    - Distribution of earthquakes and their causes
    - Destructiveness of earthquakes
  - Joints
  - Faults
- Changes due primarily to movement in the zone of flowage
  - Development of mountains and plateaus
    - Contraction of the earth
      - Folds

- Folded mountains
  - Geosynclines
  - Origin of geosynclines
  - Cause of the folding of the sediments within a geosyncline
  - Location of most intense folding
  - Size of geosynclines and of the consequent mountains
  - Rate of uplift slow
  - Flowage by recrystallization
- Plateaus
- Mountains due to faulting
  - Block mountains
  - Grabens
- Mountains due to erosion
- Mountains due to igneous agencies
  - The extrusion of lava and ash
  - The intrusion of lava
- Summary example (Appalachian Mountains)

Metamorphism

- Contact metamorphism
- Regional metamorphism
- Cleavage in slate
- Summary of metamorphic rocks

CHAPTER X

GEOLOGIC PRODUCTS OF ECONOMIC USE

Of the many and varied rock constituents found upon or within the earth an ever-increasing number are utilized by man. Most primitive men, that is, the cave men and others of the paleolithic and neolithic cultures, utilized only such dense-grained rocks as flint and basalt. The ancient Babylonians previous to 1000 B. C. made use also of copper and bronze, of clay for bricks, and of asphalt as plaster between the bricks. Gradually through the ages man utilized more and more of the substances from the earth; but it is the awakened interest in science during the last three centuries that has naturally brought about a very rapid increase in the number of earth products utilized and in new applications of those already in use. At present several hundred mineral substances contribute to our material comfort and to the business of the world, the use of one in many cases leading to the use of another. The burning of natural gas for illumination has led to the use of thorium in incandescent mantles for gas burners, as the similar application of electricity has discovered the possibilities of carbon and tungsten as light-giving filaments. Because copper is so good a conductor of electricity, and is hence used for telephone and telegraph wires, its production has of late years increased enormously.

The more important of the natural products of the earth used by man today must be briefly considered according to their mode of origin. Some are produced through the agency of forces at work at the surface of the earth; some are developed by forces resident within the earth. Among the various natural products the metals, being heavy, are naturally found deep within the earth and come to the surface or near it only when mountain-building forces produce fissures up which they may ascend as hot liquids or vapors. Later, erosion reveals to man these metal-rich fissures. The mining of minerals is thus essentially mountain work, as is expressed in the German term for mining, *bergwerk*.

NATURAL PRODUCTS UTILIZED BY MAN THAT ARE DUE TO FORCES AT THE SURFACE OF THE EARTH

Deposits formed by Mechanical Processes of Transportation and Concentration

Under the influence of rain water and other weathering agencies the surface rocks of the earth are broken down and the soluble portions, such as lime, are carried away. The more resistant particles may then be carried by streams, to be deposited in lakes or in the oceans. In this manner are formed sandstones and conglomerates, used extensively as building stones.

The heavier minerals, during their movement downstream, are frequently concentrated in the stream bed, where bends in the channel cause a slackening of the current. Such placer deposits, as they are called, contain much gold (with a specific gravity of from 15 to 19), platinum (14 to 19), and at times diamonds (3.54), while most of the accompanying sediment is made up of quartz (with a specific gravity of only 2.64) and shale fragments (still lighter). The gold that caused the rush to California in 1849 was of this type; it is likewise abundant in Alaska, the Klondike, Australia, and Brazil. But only a small part of the gold in the world today comes from placers; its original source is in most cases quartz veins. Nearly all platinum is obtained from placer deposits, and most of this from the gravels in stream courses heading up the eastern slope of the Ural Mountains, the source here being some basic igneous rocks.

Diamonds are crystallized pure carbon, though when found they are usually without crystal faces. They are probably derived from the subjection of pure carbon to intense heat; minute diamonds have thus been artificially produced. Diamonds occur in placers in many parts of the world, notably in

India and Brazil. Since the discovery of the Kimberley diamond field, in 1871, South Africa has been the chief source. In this locality the diamonds occur in volcanic necks of serpentine, in which, at the time of volcanic activity, the carbon, probably derived from the igneous rocks, was subjected to intense heat. At Kimberley the neck of serpentine has a diameter of 500 feet; it is now worked at a depth of 2000 feet.

DEPOSITS FORMED BY CHEMICAL PROCESSES OF TRANSPORTATION AND CONCENTRATION

The usual substances which are most active in waters are oxygen, carbon dioxide, sulphuric acid, ferric sulphate, hydrogen sulphide, alkaline sulphides, and alkaline carbonates. These agents not only dissolve substances from the rocks through which they pass, but cause the deposition within them of other substances, such as zinc, lead, and copper, thus bringing together very diffuse material so that it becomes of economic importance. Since most rocks are porous, with spaces between the grains and with cracks and larger fissures, and since the solutions, especially the waters rising from hot igneous rocks, are often under heavy pressures, no rock is proof against a solution of some kind, and hence they are apt to suffer chemical and mineralogical changes.

The material dissolved from rocks and carried in solution may be redeposited either at the surface of the earth or in the rocks within it.

Substances deposited at the Surface of the Earth

Sedimentary iron ores. Bog iron ores are the brown or reddish limonites so common at the edges of ponds and swamps. Waters which carry carbon dioxide from the air or from decaying organisms are capable of dissolving some iron. When the water enters the swamp, some of the carbon dioxide holding the iron in solution may escape into the air or be taken up by plant cells; thus released from the carbon dioxide, the iron is precipitated. Such bog iron ore was formerly utilized locally for the manufacture of iron.

If the iron in solution is carried into shallow bays, it will be slowly oxidized to red hematite, which will settle around calcareous shells there present or replace them; this is happening today on the south side of Molokai, in the Hawaiian Islands. Such was probably the origin of the widespread Clinton ores of the Appalachian Mountains. The Clinton formation (lower Silurian), from New York to Alabama, invariably contains one or more beds of hematite ore. These beds are being extensively worked at Birmingham, Alabama.

When plants or animals throw down matter from solution in their living activities, we have such organic types of sedimentary deposits as limestones and phosphates.

Limestones. The chemical activities of many plants and animals result in the deposition of lime carbonate as a supporting or protective tissue in such forms as corals and shells, or as separate microscopic particles. When these alone accumulate, beds of pure limestone result (see also page 234). Usually, however, waves and tides mix mud with the lime. When the mud contributes about 20 or 30 per cent of the mixture, the resultant rock is a *natural cement* (hydraulic limestone, Fig. 64). Such a rock has merely to be crushed, burned, and ground, to be ready for use as a cement.

Phosphate beds. Since the bones of vertebrate animals contain phosphorus, notable deposits of such bones form phosphate beds. Deposits consisting largely of the excrement of vertebrates, especially of sea birds, are known as *guano*. Large deposits of guano occur upon small islands off the coasts of Chile and Peru.

The ammonium phosphate from these animal remains may react with the calcium carbonate of shells, corals, and other lime deposits, forming *calcium phosphate*. For example, when such excrement is deposited upon coral limestone in wet regions, the phosphoric acid of the guano tends to replace the carbonic acid of the coralline rock, forming a phosphate of lime, insoluble in water. The small island of Nauru, 20 feet high, lying immediately south of the equator in the western Pacific, is estimated to contain 500,000,000 tons of 80 per cent lime phosphate formed in this manner, though at present birds no longer congregate there. Similar enrichment of limestone by phosphoric acid characterizes the rock phosphates of the Utah-Idaho region, averaging in thickness 600 feet, and Pennsylvanian in age. The Oligocene (Alum Bluff) phosphate deposits of Florida have probably a similar origin.

In the same way substances dissolved from the rocks may be thrown down in solid form upon evaporation of the containing water. Hence such deposits as are due to evaporation, like gypsum, salt, potassium, and boron, are characteristic of arid regions.

Fig. 64. Bluish hydraulic limestone of Devonian age, found near Milwaukee, Wisconsin

This is used for making natural cement. The beds are still horizontal as when laid down, but vertical joints have since developed. Such horizontal bedding is characteristic of the interior plains of North America. (Photograph by Alden. Courtesy of the United States Geological Survey)

Borax. Most of the world's present supply of boron salts comes from the beds of borax ($Na_2B_4O_7 \cdot 10\ H_2O$), of Quaternary age, in southern California. These were probably derived by leaching from the Tertiary volcanic material close by. The borax deposit of next importance commercially is on the border between northern Chile and Bolivia; it is being formed today by the erosion of neighboring volcanoes.

Upon the evaporation of a body of water the least soluble constituents will be the first to be precipitated. The order of the more important will be carbonate of lime (limestone), sulphate of lime (gypsum), chloride of sodium (common salt), chloride of potassium.

Table salt. Beds of rock salt usually consist of from 96 to 99 per cent of sodium chloride (NaCl). Of the 4,000,000 tons of salt produced annually in the United States very little is mined, the larger part being derived from brines formed by a solution of the rock salt by natural waters or by waters forced into the bed. A comparatively small amount is obtained by the evaporation of waters of the Great Salt Lake in Utah.

Beds of rock salt, chemically precipitated from saturated brine, are known from rocks of the early Paleozoic to the present. The Permian and Triassic, times of maximum mountains and deserts, were likewise times of maximum development of beds of rock salt. Today in arid regions, as in the western portion of North and South America, playa deposits of salt are common in the dry basins between mountain ranges.

Gypsum. Gypsum ($CaSO_4 \cdot 2\,H_2O$) occurs in sedimentary rocks from the pre-Cambrian to the present. From a saturated brine, gypsum would naturally be precipitated before rock salt (NaCl). Often, as in the Permian red beds of our southwestern states, after the deposition of gypsum, a change of climate or the incoming of the ocean has prevented the formation of salt. These beds are extensively worked, as are also those of Mississippian age in Michigan, Nova Scotia, and New Brunswick. Gypsum, ground up and known as land plaster, is used as a fertilizer. When burned at 350° F. (by which process much of the water is driven off) and then ground, it is known as plaster of Paris, from the fact that the Tertiary beds in the basin of Paris, France, are rich in gypsum. When water is mixed with this plaster, it again becomes gypsum, setting to a hard mass.

Potash deposits. These are treated in detail on page 208.

Petroleum and natural gas. Many deposits of economic value are due to the concentration of carbon and hydrocarbons derived from the chemical activities of plants and animals.

The most important of these are the gases, such as natural gas; the fluids, with petroleum alone important; and the solids, as the coals and varying mixtures of carbonaceous matter with mud, sand, or lime.

Nearly all gas and oil wells either occur in or are associated with marine strata. The gas and oil are supposed to be largely derived from bacterial decomposition of organic matter, either animal or plant; such organic remains, falling to the sea floor, are subject to the action of anaërobic bacteria, especially to that of *Micrococcus petrole*, by which their carbon is changed to a solid oil, kerogen.

The pressure and heat consequent upon deep burial transform the solid kerogen into liquid oil and gas. If a porous bed, such as one of sandstone, borders a shale bed, the water in the sandstone, especially the sea water inclosed by the sands during their deposition, forces the oil out of the shale into the sand. Since water has three times the capillary attraction of oil, the water from the porous bed is drawn into the shale, driving out the oil. This process may be observed by saturating a piece of dry shale with oil; when one end is placed in a basin of water, the oil is driven out, but under reversed conditions the oil will not drive out the water. If the region becomes folded, there is a natural tendency for the heavier water to force the oil and gas to the sides and top of the folds, and the lighter gas above the oil. Hence many wells yield in succession gas, oil, and salt water. Petroleum and natural gas are known from rocks of all periods from the Ordovician to the Tertiary inclusive. They are found upon all continents (Fig. 65).

Oil shales etc. Since carbon is usually deposited in minute particles, it is in the shales, aside from coal deposits, that most comes to rest. Consequently black shales are abundant, and where the carbon has become changed to hydrocarbons, as noted under Petroleum, oil shales result. Such oil shales are very abundant upon every continent, and form an almost inexhaustible oil reserve that can be utilized when less expensive methods are developed for its extraction. From such oil shales the hydrocarbons (made liquid through the heat due to pressure of overlying sediments) may be forced into sandstones and into porous limestone, where it may form oil pools or, gradually losing its lightest elements, solidify, giving rise to combinations of asphaltum with limestone, sandstone, or earth, as the case may be. Many rich deposits of this last type — asphaltum mixed with mud and sand — are abundant on the island of Trinidad and on the neighboring mainland of Venezuela. These deposits of Tertiary age contain one third sand and clay, one third water, and one third bituminous matter. At Rancho la Brea, near Los Angeles in California, a deposit of similar age formed a death trap for thousands of organisms during the Pleistocene. Many mammals and birds, probably attracted by pools of water upon the surface of the asphaltic earth, were held fast by this tarry mass, while other animals, coming to prey upon these, were similarly entrapped; then followed death, decay of the flesh, and downsinking of the bones into the mass. Probably the largest known deposit of asphaltic sand occurs along the Mackenzie River in northern Alberta.

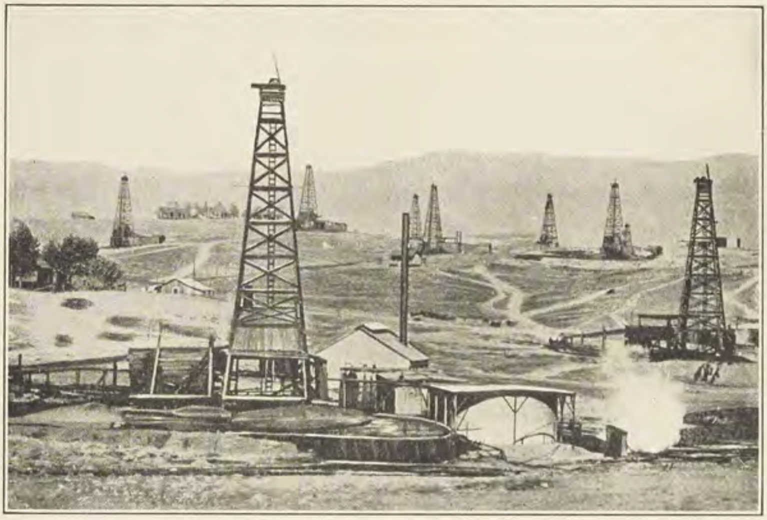

Fig. 65. Derricks over petroleum wells in the Coalinga district of southern California

Petroleum wells are sunk in the same manner as artesian wells. (Courtesy of the United States Geological Survey)

Coal (Fig. 66). Carbonaceous matter may accumulate in any swamp or peat bog where the growth of new vegetation exceeds the complete rotting of the old growth, that is, in localities and under circumstances where not all the carbon of the vegetable tissue has been oxidized. If this becomes subjected to sufficient pressure, a coal bed may result. It is only in regions near sea level, where, after the accumulation of much carbonaceous material, a slight sinking may naturally occur, letting in the sea with its accompanying sands or muds, that preservation of the carbon for any length of time is at all likely to take place. Repeated oscillations would result in a succession of coal beds. Periods of increased rainfall or a slight uplift of the bordering lands would cause the streams to bring in more mud and sand, producing shaly partings in the coal beds. The vast majority of such deposits now forming (one seventh of Ireland is covered by peat bogs) either never become covered

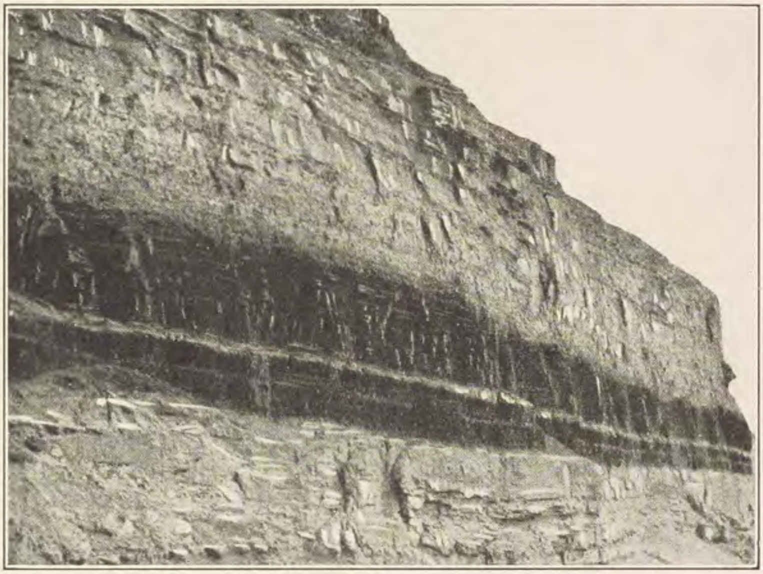

Fig. 66. Eight-foot coal seam including two clay layers in its lower portion, near Glendive, Montana

Photograph by Campbell. Courtesy of the United States Geological Survey by sufficient sediment to preserve this accumulation of carbon, and to subject it to pressure adequate to convert it into coal, or they are so mixed with mud brought in by streams as to result in a bed of black shale. Today almost the only swamps fulfilling the proper conditions for the formation of coal beds are either in temperate or, more especially, in tropical regions.

Fig. 67. A characteristic view of Dismal Swamp, Virginia, showing the typical vegetation, including cypress trees

Photograph by Russell. Courtesy of the United States Geological Survey

On the island of Sumatra in the East Indies a bog covering three hundred and twelve square miles has a deposit of compact peat, made up of decaying leaves, twigs, and logs, reaching a thickness of thirty feet, which could make a seam of coal nearly three feet thick (Potonié). Similar tropical swamps exist in Africa and South America.

The *Great Dismal Swamp* of Virginia and North Carolina is another example of a potential coal field. It lies but slightly above sea level, at parallel 36°, with an annual precipitation of about 54 inches and an average humidity of 73 per cent. Thus favored by warmth, a long growing season, and a well-distributed rainfall, plant growth is abundant. Upon the undrained 1500 square miles of this swamp the peat varies from one to twenty feet in thickness. This peat is being formed from the arrested decomposition of the leaves, twigs, roots, and trunks of aquatic plants and of mosses, ferns, herbs, shrubs, and trees. It is coal in the process of formation (Osbon). (Figs. 67, 68.)

Fig. 68. Lake Drummond in the central part of Dismal Swamp, southeastern Virginia

Note the cypress trees growing within it and their abruptly expanded base. (Photograph by Russell. Courtesy of the United States Geological Survey)

In the formation of coal the atmospheric oxygen is largely excluded by the moisture, and change from woody fiber to coal is merely the giving off of such products as water (H_2O), carbon dioxide (CO_2), and methane, or marsh gas (CH_4), with a consequent proportional increase in carbon, for the evolution of water and methane exhausts the hydrogen more rapidly than the carbon. Wood that has 22 per cent of carbon when sound has 31 per cent when rotten. According to Renault the change is as follows: Cellulose, that is, woody fiber $(C_6H_{10}O_5)_4$ = bituminous coal (C_9H_6O) + marsh gas $7(CH_4)$ + carbon dioxide $8(CO_2)$ + water $3(H_2O)$. The successive stages are peat, lignite, bituminous coal, anthracite, and graphite. That at least many coal beds were formed in the place of growth in swamps is evidenced by the numerous trees with roots in the underlying old soil (now fire clay). Leaves, twigs, and (especially where the vegetation consisted largely of ferns, horsetails, or club mosses) large numbers of spores would drift and sink in the more open portions within the lakes in these swamps, forming pure coals such as cannel coal. The Carboniferous forests, which, under the widespread swamp conditions, gave rise to the greatest development of coal the earth has known, were essentially pteridophyte forests; that is, they were made up mostly of club mosses, horsetails, and ferns. Today plants of these classes, especially the first two, though they are of small size, develop great quantities of pollen. That the trees (50–100 feet high) of these types of plants developed in the Carboniferous immense quantities of pollen their well-preserved cones, packed with male and female spores, abundantly testify. That these spores contributed largely to the accumulation of the coal is borne out by the work of Jeffrey on the study of thin sections of coal, for many of these sections are composed almost entirely of spores (Fig. 69).

Fig. 69. Carboniferous cannel coal enlarged five hundred diameters

The numerous white flattened oval bodies are spores and the remaining, darker bodies are highly carbonized microscopic particles of wood. (Photograph by E. C. Jeffrey)

Thus, apparently, the factors necessary for the accumulation of carbon to a sufficient amount to form beds of coal are (1) a wet climate both for rapid growth of plants and for their preservation under water; (2) lands near sea level, so that their depression may be likely to cause an extension of sediment over the peat by the revived streams from the high lands. Whether the ocean is extended over the peat beds depends upon whether the sediment brought in by the streams is sufficient to exclude the sea or not. The essential point is the covering of the peat to a sufficient depth to reduce its oxidation to a minimum. In a cold climate the decay of the vegetation is less rapid, while in a warm one growth is more rapid.

Except for minute spores, fossils in coal after it has reached the bituminous stage are rare because of the great amount of decay and of later pressure exerted upon this plastic mass of carbon. In the slaty partings or in the roof shales fossils are numerous, as here the great amount of mud or sand makes the material more firm. That numerous plants were present in the coal itself in its very early stage is shown by their wonderful preservation in the coal balls, — concretions of lime ($CaCO_3$) or of iron ($FeCO_3$ or FeS_2) formed before the plants had become much macerated. Furthermore, the slickensides upon the sides of these balls indicate that after their formation a great amount of movement had taken place within the coal bed.

Though a few anticipatory thin seams of coal are known from the upper Devonian of Russia and Norway, the vegetation of the earth had apparently become sufficiently evolved in amount of woody fiber formed, and in rapidity of growth and of multiplication, only by Mississippian time, to be capable, under proper topographic conditions, of forming deposits of peat faster than its decay. Economically important coal beds are known from every period from the Mississippian to the Tertiary inclusive. Very little developed during the Pleistocene, because it was a time of high lands, and for the same reason little is developing today. The greatest deposits of coal were formed during the Pennsylvanian and Cretaceous, following the widespread withdrawal of the seas from the continents and preceding the world-wide formation of mountain ranges, processes naturally accompanied by the warping of land surfaces, with the consequent widespread formation of low-lying swamps.

That the concentration in carbon is not due to the duration of burial is indicated by the existence of bituminous coals within all periods from the Mississippian to the Tertiary inclusive; lignites are similarly known from these periods. The older rocks, having been subjected to more movements than later ones, naturally have a much larger proportion of anthracite and bituminous coals.

The principal conditions necessary for changing woody fiber into coal are as follows: (1) The amount of decay before deep burial. If the mass is largely one of minute carbon particles, the change to coal is largely a matter of pressure. (2) The pressure and heat due to folding. Anthracite is nearly always found in mountains, and bituminous and lignite coal in mountains or upon the plains. The anthracite of the Allegheny Mountains changes into bituminous coal westward in the flat-lying strata of the Allegheny plateau. (3) The depth of burial, which affects pressure. (4) The presence of joints, which permits the escape of gases.

The more finely divided fuels, as peat, lignite, or coal dust, are usually mixed with pitch or asphalt and pressed into briquettes before using. Coal, though used to some extent in early historical times, did not become important to man until after the invention of the steam engine.

Substances deposited in Rocks beneath the Surface of the Earth by Concentration of Materials contained within the Rock itself

Iron ore. Concentration may be due to the decay of rocks at or near the surface of the earth. Since during the weathering processes only a small part of the iron present is carried away in solution, if the original rock contains a considerable number of iron-bearing minerals the result will be the accumulation of a residual deposit of limonite intimately mixed with clay. Iron ores of this derivation are abundant in the southern Appalachians.

The iron ore of the Lake Superior district in Minnesota, Wisconsin, Michigan, and Canada appears to have had a similar origin. Deposited largely in Proterozoic times as ordinary sediment rich in iron, it was later concentrated by the leaching out of much silica and at the same time was largely oxidized to hematite. Such leaching and oxidation from the surface to great depths could apparently occur only during a time of great aridity, when the water level was exceptionally low. This concentration must have occurred in pre-Cambrian times, as fragments of ore are found in the Cambrian sediments. The iron ores mined in the Lake Superior region amounted, in 1917, to 64,000,000 long tons; this represents from 80 to 90 per cent of our domestic output.

Sulphur. The deeper-seated ground waters may likewise bring about concentration of substances of an economic value to man. Though native sulphur of economic importance has accumulated in the necks of volcanoes, as in Japan and the South American Andes, or at the edge of hot springs (from California to Wyoming), the greater part is not connected with volcanic processes. It is usually obtained from sedimentary beds, closely associated with gypsum, from which the sulphur has probably been derived through the reducing action of organic matter. Most of the sulphur of commerce today comes from the upper Tertiary sedimentary rocks of Sicily, and especially from the Tertiary and Cretaceous beds of the Gulf coast of the United States. Sulphur is used largely in the manufacture of sulphuric acid, of sulphur dioxide for bleaching purposes, and of gunpowder and matches.

Lead and zinc. It is usually considered that the lead-zinc ores of the Mississippi Valley have been concentrated by circulating waters, either ascending or descending or both, and leached from the surrounding Paleozoic rocks. These deposits are in joints and along stratification planes within a few hundred feet of the surface, especially just below relatively impervious shale beds. The ores occur in the usually flat-lying limestones of the Paleozoic (the Ordovician to Mississippian inclusive), in the region extending from Oklahoma to western Virginia and north into Wisconsin. The Joplin region of Mississippian age, in southwestern Missouri and adjacent parts of Oklahoma and Kansas, is especially noteworthy.

NATURAL PRODUCTS UTILIZED BY MAN THAT ARE DUE TO FORCES WITHIN THE EARTH

Deposits due to Contact or Regional Metamorphism

Under the intense pressure of mountain-folding, with the consequent increase in heat, the clay and shales may be changed to slates, sandstones to quartzites, limestones to marbles, various iron ores to magnetite, and bituminous coal to anthracite or even to graphite. An intrusion of large masses of hot igneous rocks into sediments may produce similar results (see Metamorphism, p. 139). The graphite of the Adirondack Mountains in New York State occurs in highly metamorphosed sediments. At present the largest supplies of graphite come from Ceylon and Madagascar. Serpentine, talc, and asbestos are developed in a similar manner.

Deposits due to the Introduction of Substances Foreign to the Rock and usually associated with Molten Rock from within the Earth

Waters ascending from igneous rocks within the earth are frequently rich in sodium carbonate but poor in silica and calcium. Hence they attack silicates and limestones with great energy. Since at the same time they usually contain many of the rarer substances such as boron, fluorine, iodine, arsenic, gold, silver, mercury, tin, as well as copper and lead, they are apt to deposit these together with the quartz and lime, forming ore-bearing veins, such as gold-quartz veins; for rocks are full of fissures, due to jointing, faulting, or the cooling of igneous rocks, along which these waters may move, usually with a certain amount of deposition of their inorganic content. These circulating waters may even deposit some ores at the surface of the earth, as in the hot springs in New Zealand, where gold, silver, and mercury are now being deposited in association with chalcedonic quartz. Usually, however, through loss of heat, lessened pressure, and other causes, the solidification point of the various substances is reached at varying distances below the surface.

Surrounding the Pacific Ocean, in the so-called "circle of fire," there were poured forth and intruded during the Tertiary period of earth history enormous quantities of molten rock, much of which has since been eroded to a depth of a few hundred feet or more. These rocks, in western North and South America, in New Zealand, in the East Indian islands, and in Japan, are the source of much of the world's present production of gold, silver, mercury, and copper. Similar ore deposits are found in the rocks of all periods. The gold-quartz veins of the Sierra Nevada Mountains, the source of the placer gold of California, were formed during the late Jurassic, and those of Victoria, Australia, probably during the Ordovician.

One of the substances deposited at great depths within the earth is tin. Most of the present supply of tin comes from the Malay Peninsula and the adjacent regions; much is also obtained from Bolivia. The tin deposits of Cornwall, southwestern England, have been worked since the time of the Phœnicians and still yield a considerable supply.

Some of the latest deposits to form in a large intrusive mass are pegmatite dikes. These are formed of the residual portions of the magma, are coarsely crystalline, and frequently contain deposits of economic value, such as feldspar, mica, tin, tungsten, tourmaline, uranium, thorium, and many other minerals.

TOPICAL REVIEW

Natural products utilized by man that are due to forces at the surface of the earth
  Deposits formed by mechanical processes of transportation and concentration. Sandstones, conglomerates, gold, platinum, diamond
  Deposits formed by chemical processes of transportation and concentration
    Substances deposited at the surface of the earth
      Sedimentary iron ores. Bog iron ore, or brown limonite, hematite
      Limestones
      Phosphate beds
      Borax

        - Table salt
        - Gypsum
        - Potash deposits
        - Petroleum and natural gas
        - Oil shales etc.
        - Coal
    - Substances deposited in rocks beneath the surface of the earth by concentration of materials contained within the rock itself
        - Iron ore
        - Sulphur
        - Lead and zinc
- Natural products utilized by man that are due to forces within the earth
    - Deposits due to contact or regional metamorphism. Slate, quartzite, magnetite, marble, anthracite, etc.
    - Deposits due to the introduction of substances foreign to the rock and usually associated with molten rock from within the earth. Gold, silver, mercury, tin, copper, etc.

STRATIGRAPHIC HISTORY OF THE EARTH

[The sequence of events resulting from the interaction of the forces at the surface of the earth and those within it]

CHAPTER XI

STRATIGRAPHIC FACTORS AND TIME MEASUREMENT

The earth may be considered to have had a stratigraphic history from the time when it first became subject to erosion by water. Thence followed a succession of events due to the interaction between the forces operating at the surface of the earth and those originating within. Water and air, set in motion by the sun's heat, the force of gravity, and the earth's rotation tend continually to wear down the high lands and transport their constituents to lower levels. On the other hand, the forces of the earth's interior expressed in varying stresses of heat and pressure are constantly readjusting the rocks below the surface, pushing up some areas and pulling down others. The succession of events due to the interaction of these forces is known as stratigraphic, or historical, geology.

SEDIMENTS

The rock particles torn by the rain, wind, and ocean waves from the land find lodgment again in lower-lying areas. This sediment possesses differing characteristics according to its derivation and its manner of deposition.

Stratified deposits. Sediment is usually laid down in water or from moving air, through which the force of gravity may easily express itself. The heavier particles are pulled down first, the finer coming to rest later. The result is a layer made up of coarser particles overlain by finer. A succession of storms produces a succession of thin layers, or laminæ. Successive varying climatic conditions are recorded in the character of successive varying layers. Some greater change in physical conditions may close this sequence and begin another, thus delimiting separate beds, or strata (Fig. 70). When sediment is laid down thus in strata, it is said to be stratified (Fig. 64).

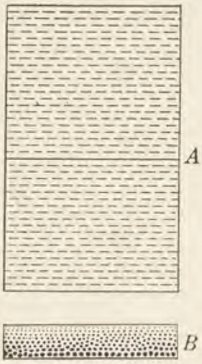

Fig. 70. Stratification

A, two strata, each made up of many laminæ. *B*, one lamina enlarged; this represents the deposit due to one great storm or, more usually (in the ocean), to the restirring of the mud upon the floor by exceptionally strong storm winds. Thus, because of a decrease in the strength of waves or currents, many years may elapse between the formation of successive laminæ. The close of one stratum indicates some radical change, such as a shifting of currents, the rise or fall of the deposition area, etc.

Unstratified deposits. When sediment is deposited without the sorting action of gravity, coarse and fine particles are thoroughly mixed. The principal agents of this type of deposit are glaciers, landslides, and avalanches. It is at times difficult to determine the origin of ancient deposits of this type.

What sediments tell us. The sediment of upper Cambrian age at the eastern foot of the Adirondack Mountains, in New York State, is a thinly and evenly bedded shaly sandstone inclosing marine organisms both small and large. Upon the surface of many beds are trails of marine animals, ripple marks, mud cracks, and raindrop impressions. These sediments thus tell us that in those ancient times the sun shone, evaporating some of the water then present, and that winds carried it over the land, where it was precipitated in the form of rain; that the carbon dioxide caught by the moisture weathered the solid rocks; and that the run-off of the rain forming the streams carried the weathered particles to the ocean; that in the ocean waters they were laid down, layer upon layer, under the action of gravity, the evenness of the beds attesting that neither waves, currents, nor tides were stronger than those of today; that upon the retreat of the tide marine animals left their trails upon the muds in the shallowing waters, as they do today upon our coasts; that, exposed to the sun at low tide, these trails became hardened, as were also the ripple marks made by the winds and retreating waters; that during low tide, while the air and sun were drying the muds, with the consequent formation of mud cracks, a passing cloud gave rise to a slight fall of rain, after which the pit formed by each falling raindrop was similarly hardened. Upon the return of the tide with its sediment some of the trails, ripple marks, mud cracks, and raindrop impressions were gently covered with mud and sand and thus preserved. Judging from the size and abundance of the organisms in this ocean, and their relation to forms living today, the waters and consequently the air must have been as pure as they are now, with no appreciably greater amount of carbon dioxide or other deleterious gases than now exists. Thus these sediments disclose a physical world of those far-off days much like our own today, while their present position tells us of vast changes in the relation of land to ocean; for they show that the floor of this ancient ocean was gradually sinking, permitting a thick accumulation of sediment, and that much later it was raised from its ocean home, attacked by the forces at the surface of the earth, and worn down, exposing the various beds as they are seen today.

Color of sediments very significant. 1. *Dark or gray.* Dark or gray sediments are due to the presence of innumerable minute particles of carbon. Such sediments indicate that they were deposited in lakes or oceans, where the comparative rarity of the bacteria of decay, which require a great amount of free oxygen for their work, permitted the preservation of much of the organic matter.

2. *Yellow or red.* When sediments are deposited in temporary bodies of water, such as those caused by rivers which overflow their banks, in playas, etc., the organic matter, upon the disappearance of the water, will be attacked by the bacteria of decay and the free oxygen of the air and will return to the atmosphere mainly as carbon dioxide (CO_2). Since iron is present in very many sediments in the form of

iron carbonate, this will, upon the removal of the carbon, enter the ferric state. Hence, upon the disappearance of all carbon the residual sediment will be yellow. With the disappearance of the water, in turn, the iron will become red. Where there is a heavy and evenly distributed rainfall, with a consequent rapid growth of plants, new carbon particles are continually being added; yet in spite of this addition much of the soil and newly added sediment of the Gulf states is reddish. Such beds are forming in deserts today, as in the past. Huntington records how the sand in the Transcaspian and Takla Makan deserts of southwestern Asia regularly changes from the brown of the more recent deposits upon their borders to the pale red of the older deposits far out in the desert. Hence a red clay or sand rock without marine fossils is merely an indication that it was deposited upon the land,—that it is a continental deposit; it tells nothing of the climate. When, however, the red beds are accompanied by deposits of salt or gypsum, as is often the case, the climate is shown to have been undoubtedly arid. Continental red beds are known from substantially all periods of earth history, from next to the earliest (the Proterozoic) to the latest. (For red beds formed in ocean waters see page 146.)

FOSSILS

As sediment slowly settles it tends to bury whatever plant or animal remains are present. These are naturally abundant in lakes or shallow seas, though even here nearly all soft parts, such as flesh, have been previously destroyed by other animals or bacteria. Many of the harder parts, such as shells, bones, and woody fiber, also disappear under the solvent action of many of the waters, the action of currents and waves, and the boring of worms, sponges, etc. The organic remains which escape destruction are known as fossils. A *fossil* may be defined as an organism, or anything indicating the former presence of an organism, which has been preserved in the rocks.

In almost all cases it is only the hard part, the skeleton or shell or woody fiber, that is preserved. Very rarely indeed is the flesh preserved. Some specimens of an ancient elephant, the mammoth, have been found intact in the frozen earth of Siberia. Usually the hard parts themselves are changed. Through the agency of water charged with various chemical substances and circulating through the outer rocks of the earth the pores in shells or bones become filled with mineral matter, or the entire structure is replaced. Thus the original lime carbonate of a shell may be replaced by silica or by iron oxide, and wood may be replaced by silica (Fig. 71). Through the giving off of more hydrogen and oxygen than carbon by many organisms, as happens under water, there results a concentration of carbon, producing carbonized plants, fish, etc. (Fig. 72).

Fig. 71. Section of a small silicified tree, showing the original growth rings

As a molecule of the wood (in the gaseous state) was removed, the percolating waters deposited a molecule of silica in its place

Footprints (Fig. 73) of amphibians, reptiles, birds, and mammals, trails of mollusks and crustaceans, burrows of worms and sea urchins, and such structures as birds' nests, implements, and coins give indication of once active organisms. When a shell inclosed in a rock is removed by percolating waters, it leaves a mold of itself. (The original shape and surface ornamentation of such molds may be reproduced by the use of dental wax or soft plaster of Paris.) In this way have been preserved the shapes of several men and dogs buried under the volcanic ash that overwhelmed the town of Pompeii during the eruption of Mount Vesuvius A.D. 79.

Conditions necessary for the preservation of fossils. The conditions necessary for the preservation of fossils are (1) the presence of hard parts and (2) a speedy entombment within some protective material. Since the basis of both animal and plant life is the jellylike protoplasm, it is natural that only the supporting and protective structures of this protoplasm, such as shell, bone, and cellulose, can usually be preserved. The freely circulating oxygen in deposits upon land tends quickly to destroy all dead organisms, and it is only by the rarest of accidents that a land animal is carried to a lake or ocean. Fresh-water deposits may preserve organic remains for a limited time; but even the largest lakes are, geologically speaking, quickly destroyed with all their deposits. Under normal conditions, therefore, it is only in the ocean that dead organisms stand much chance of being preserved for long periods.

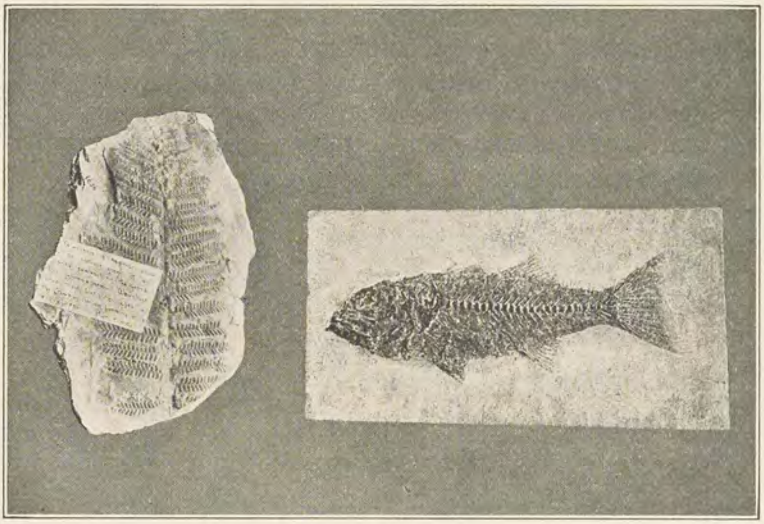

Fig. 72. View of two carbonized organisms

The frond of the Pennsylvanian seed-fern, Pecopteris, from Pennsylvania; an Eocene fresh-water fish, Mioplosus, from Green River, southwestern Wyoming

Proportion of plants and animals preserved as fossils. It follows from the conditions outlined above that the possibility that an organism will become a fossil varies with its habitat (Fig. 74). Very few land-dwelling forms are preserved, as most of these die at a distance from large bodies of water and fall a prey to scavengers, so that they are never buried in sediment. Hence there are comparatively few fossil men, birds, and monkeys, more insects, lower mammals, and reptiles, still more fresh-water shells and fish, and an abundance of bottom-dwelling marine forms, such as shells and corals. Yet even the number of these marine forms preserved as fossils, compared with the number living in the world at the time, must be incalculably small. Moreover, after their preservation in the sediment the probability of their being found by man is exceedingly remote. The rock in which they lie embedded may never be raised so that erosion can set them free, and even when they are thus attacked it is only in widely separated places, such as the rocky banks of stream courses, that they become sufficiently freed from the concealing soil to give evidence of their presence. Finally, it is only when a man interested in them happens to arrive at the place as the fossils are beginning to weather out that they may be studied. To this must be

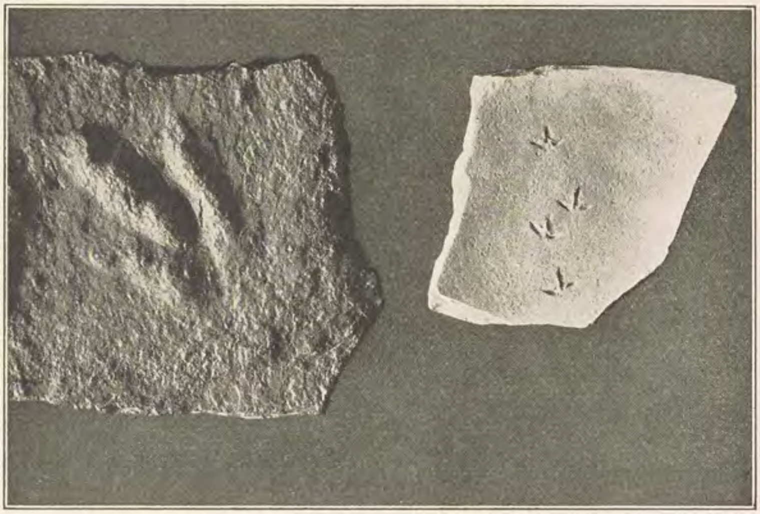

Fig. 73. Footprints

At the right are modern bird tracks in the mud of the Bay of Fundy; at the left is a reptile track (in reverse) in the Triassic muds of the Connecticut River valley added the fact that very many of the fossil-bearing rocks have been disintegrated through erosion during the millions of years of earth history, or have had their fossil contents destroyed through the metamorphism of the inclosing rocks. Williston expresses the conviction that we can never hope to find even a single fossil of perhaps the majority of species of animals and plants that have lived on the earth, most of which must have numbered many millions of individuals.

What fossils tell us of the once living animal. A single complete skeleton reveals much. The number and arrangement of the bones classify it as fish, amphibian, reptile, bird, or mammal. The size of projections, roughened surfaces, or depressions on the bones indicate the number and size of the muscles attached to them, and the number, size, and arrangement of the bones and muscles suggest the size and shape of the animal. The shape of the teeth discloses the nature of the food, and this reveals the size and character of the digestive organs. Sharp, cutting teeth (Fig. 75) indicate a flesh diet, and flat-crowned teeth, usually a plant diet (Fig. 76). Thus the teeth, limbs, and muscles reveal rather clearly the size, shape, food, and habits of the animal, and somewhat of its habitat. The habitat is also partially indicated by the nature of the sediment inclosing the fossil. The superficial covering (skin, scales, hair, etc.) is usually preserved in fish but comparatively seldom in reptiles, birds, and mammals. The prob-

Fig. 74. The probability that an organism will become a fossil varies with its habitat

Few of the animals or plants living in the area of erosion could be preserved. A very few would find lodgment in the temporary lakes; still fewer would be carried by the streams to the ocean. The organisms living upon the floor of the shallow ocean would stand the best chance of survival

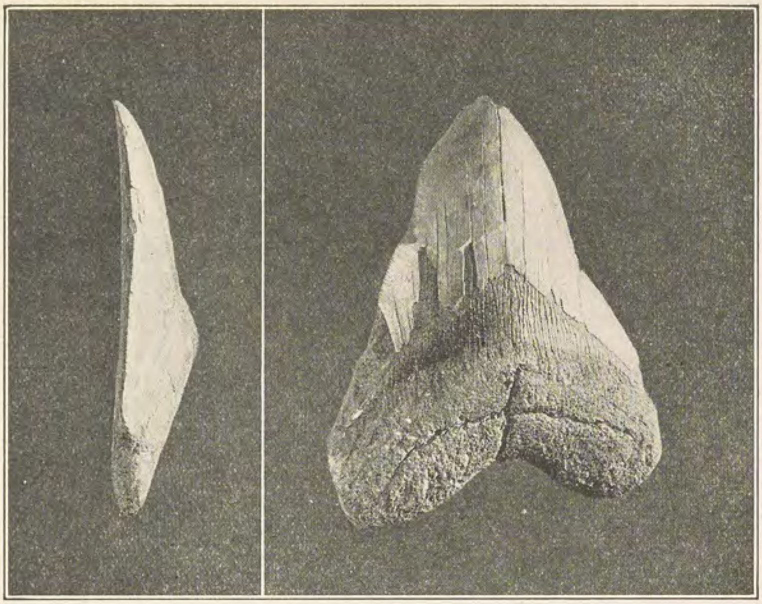

Fig. 75. Carnivorous teeth

Front and side views of two teeth of the huge Eocene shark, *Carcharodon megalodon*

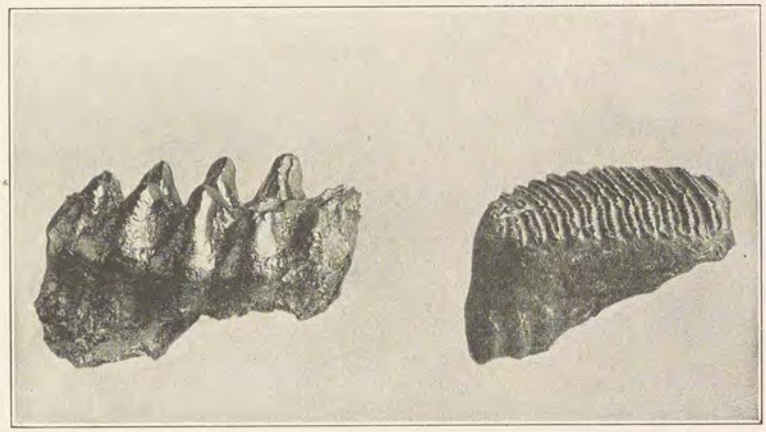

Fig. 76. Herbivorous teeth

At the left a single tooth (eight inches long) of the mastodon from South Carolina. At the right a single tooth (six inches long) of a true elephant (Elephas) from South Carolina. Both these elephants were very abundant throughout North America during the Pleistocene able covering of the last three classes is usually conjectured through a comparison with the nearest living relative in a similar habitat.

In regard to the invertebrates (animals without a backbone), the habitat, food, and habits are likewise inferred from the shape of the fossil, the inclosing sediment, and the nearest living relatives. Since all corals, crinoids, starfish, sea urchins, and brachiopods live today in the ocean, their ancestors are supposed to have had a similar habitat, and all other facts derived from a study of sediment and life support this conclusion.

SUBDIVISIONS OF EARTH HISTORY

Basis of subdivision. The sediment laid down in a lake or ocean this year naturally rests upon the sediment deposited last year, and this in turn upon successively earlier layers. Later deposits always rest upon older deposits, except in unusual cases in which they have been overturned in mountain-folding. Such overturned rocks are, as a rule, easily identified by the change in the rock itself, due to the intense pressure and consequent heat. Hence, *of any two sedimentary rocks the one that was originally the lower is the older.* With the order of formation of the rocks in time once established, the records inclosed by them — fossils, mud cracks, color of sediment, lava flows, folding, and faulting — can be correctly interpreted as to the time of their occurrence.

As the fossils, the records of the plant and animal life of the earth, are studied it is seen that those from the oldest rocks, that is, the sediment deposited in the earlier days of the earth's history, differ greatly from the life of today. When the fossils are arranged on our museum shelves, in order, from those taken from the oldest rocks to those forming today, it is seen that throughout earth history the plants and animals have been continually changing. The change was from simple, lowly forms in the early years to the complex, highly developed organisms of today. This holds true for all continents. This constant change in the life of the earth, as exhibited in the sedimentary rocks from the oldest to the present, forms the principal basis upon which earth history is divided into eras and periods. Life has written its own history upon the record sheets of the strata. Though man's ability to interpret these records is as yet imperfect, it is improving with the years. It is the work of the paleontologist and geologist to read these sheets and, where one is missing, to search for it in some other continent. Upon no land is there exposed a section giving a continuous record of deposits from the earliest days of earth history to the present. Many mountains, like the Appalachians, exhibit most of the Paleozoic; others, like the Alps, reveal most of the Mesozoic. The final history is a patchwork, like human history or the history of any single nation; and as in human history a greater lapse of time is lumped into each of the earlier periods, and less space taken in telling of it, so it is with earth history; for what happened yesterday is of greater interest than what happened one hundred years ago, and we know more about it. In brief, the basis for the subdivision of earth history is the deposition of sediment, layer upon layer, giving the correct sequence in time. With this time card established, it is comparatively easy to place in their correct historical positions the remains of life and the physical records inclosed by or impressed upon these sediments. Thus the biography of the earth, which man is slowly deciphering, is written within and upon it.

Subdivisions. Earth history is divided into eras, which are in turn subdivided into periods. The names of eras refer to the type of life present upon earth at the time, in comparison with that of today. Each name is derived from two Greek words, the latter of which, *zoē*, means "life,"— *Archeozoic* (ancient life), *Proterozoic* (former life), *Paleozoic* (old life), *Mesozoic* (middle life), *Cenozoic* (recent life). The names of the periods usually refer to the locality where the rocks of the particular period were first thoroughly studied. Thus, *Cambrian, Ordovician,* and *Silurian* have reference to Cambria (Wales) and to the ancient British tribes, Ordovices and Silures, of the surrounding region; *Devonian* refers to the county of Devon, England; *Mississippian,* to the middle Mississippi Valley; *Penn-*

sylvanian, to the state of Pennsylvania; *Permian,* to the province of Perm in eastern Russia; *Jurassic,* to the Jura Mountains. The other period names have various origins. *Carboniferous,* the combined Mississippian and Pennsylvanian, means "carbon-bearing" and refers to the great amount of coal found in the rocks of that period. *Triassic* refers to the threefold development of rocks of this age in southwestern Germany—sandstone at the base, then limestone, with clay above. *Cretaceous* refers to the fact that these rocks in western Europe contain much chalk (Latin *creta,* chalk). The names of the latest periods are each made up of two Greek words; the latter (*cainos,* recent) refers to the present life of the earth, while the former refers to the proportion of fossil species that have living representatives. Thus from 20 to 40 per cent of the species fossil in the Miocene rocks are living today. *Paleocene* means "ancient recent life"; *Eocene,* "the dawn of recent life"; *Oligocene,* "few recent species"; *Miocene,* "a great number of recent species"; *Pliocene,* "still more"; and *Pleistocene,* "the largest number of recent species"; while *Holocene* (entirely recent) is "today." *Tertiary* and *Quaternary* are survivals of a much earlier classification, which divided earth history into four periods—*Primary* (ancient primitive rocks), *Secondary* (our Mesozoic), and then *Tertiary* and *Quaternary,* used with the same significance as today.

AGE OF THE EARTH IN YEARS

Probably the oldest living things in the world are trees. In one sequoia from California John Muir counted more than 4000 rings, giving it an age of over 4000 years; some baobab trees of Senegal and the Cape Verde Islands are upward of 5000 years old; but probably the oldest so far recorded is the bald cypress in the village of Santa Maria del Tula in southern Mexico. This tree, held sacred by the inhabitants, has a circumference of 126 feet, four feet above the ground. The cypress is a slow-growing tree. Asa Gray found one 14 feet in circumference to be 670 years old, and the Del Tula cypress, which still shows no signs of decay, he estimated as between

TABLE XI. SUBDIVISIONS OF EARTH HISTORY

Eras are distinguished by world-wide changes in relation of land to sea and by marked changes in plants and animals. Periods are separated by less marked changes

ERAS			PERIODS	CHARACTERIZED BY		DOMINANT LIFE
CENOZOIC	QUATERNARY		Holocene Pleistocene (Glacial)	Modern plants and animals World-wide glaciation; most severe in North America and Europe		Age of man
	TERTIARY	*Late*	Pliocene Miocene	World-wide elevation of mountains, continuing through Pliocene		Age of mammals and of flowering plants
		Early	Oligocene Eocene Paleocene	Incoming of modern mammals Archaic mammals		
MESOZOIC	LATE		Upper Cretaceous Lower Cretaceous	Great development of coal and chalk Extended submergence of all lands Earliest known flowering plants Largest land animals (dinosaurs)		Age of reptiles and of primitive flowering plants
	EARLY		Jurassic Triassic	First known birds Red beds, salt, gypsum		Age of reptiles and of medieval floras
PALEOZOIC	LATE		Permian *Carboniferous* Pennsylvanian Mississippian	World-wide glaciation; most severe in Gondwana World-wide upheaval of mountains continuing through Permian Greatest coal-producing period Maximum development of fixed echinoderms (crinoids, blastoids)		Age of amphibians and of ancient floras
	MIDDLE		Devonian Silurian	Lungfish and ganoids dominant Incoming of fish and land plants		Age of fishes and primitive land plants
	EARLY		Ordovician Cambrian	Earliest well-developed oil and gas First definitely known marine faunas		Age of invertebrates and water-dwelling plants
PROTEROZOIC (Algonkian)	LATE	*Periods not definitely known*		World-wide glaciation Huge iron and copper deposits in Lake Superior region Earliest known glaciation	Sediments like Paleozoic and later rocks; only locally metamorphosed	Age of primitive water-dwelling plants and invertebrates
	EARLY					
ARCHEOZOIC (Archean)	LATE				Sedimentary and igneous rocks intensely metamorphosed	Age of one-celled plant-animals
	EARLY			Birth of water and atmosphere, oceanic depressions, and continents, sediments, and first life		
COSMIC				Earth with molten exterior Birth of earth (through tidal disruption of ancestral sun) Evolution of nebula to sun		

5000 and 6000 years old. If the Del Tula tree is of this age, it was several hundred years old when Cheops built the Great Pyramid in Egypt; it was flourishing during the rise and fall of ancient Nineveh and Babylon, for the earliest cuneiform inscriptions unearthed in Assyria date back only to 1800 B.C.; it had flourished upward of 2000 years when the Hebrews left Egypt; that is, all human history since man began to make dependable records is spanned by the life of a single tree. Yet the life of even this Methuselah among trees is but an episode compared with the time occupied by the erosion to sea level of a land area upon which the trees grow; and many times throughout earth history high mountains have been thus leveled.

To get some idea of the age of the earth, everyone, as Darwin says, should watch for himself rivulets bearing down mud, and waves wearing away sea cliffs, and then examine the great piles of sedimentary rocks, many miles in thickness. He should also note what slight changes in heights of land are recorded in human history, and then recall within how recent geologic times the great mountains of today were still beneath the ocean waters. The Alps were raised from their ocean bed during the Oligocene, while the Himalayas left their marine birthplace during the Miocene. But it was only during the Pliocene that the latter attained to their present height; after the beginning of the Pliocene, under such a very slow upward movement that the Sutlej River could continue cutting through the rising mountains, the Himalayas were elevated from sea level to a height which the great subsequent erosion has been able to reduce only to 29,000 feet.

Many methods for reducing this time to terms of years have been devised. The two following are considered the most important thus far developed for estimating the age of the earth since its surface became solid and its erosion by water and wind active. (For an additional method applicable only to more recent times see Fig. 113.)

Deposition and erosion method of estimating the age of the earth. This method compares the rate of deposition today with the total thickness of sedimentary deposits formed throughout earth history. The landward portion of the delta of the

Nile River is, according to Lyons, raised at the rate of 34 inches a century through the deposition of a part of the 51,428,500 metric tons of earth that it carries in suspension each year. The sedimentary rocks of the world, from the oldest known to the present, have a maximum thickness of about 350,000 feet. If this pile of sediment were deposited continuously and at the present rate of the Nile delta, it would require 12,000,000 years.

The deposition of this vast column was, however, by no means continuous. Lost intervals for which there are no known deposits are numerous. Several of these were sufficiently long for the elevation of great ranges of mountains and their subsequent erosion to a low plain. Now these mountain ranges were the highest parts of the continent, and an erosion to sea level would doubtless be as slow a process as the erosion of the present United States to a low plain. The work of the Hydrographic Branch of the United States Geological Survey shows that 270,000,000 tons of dissolved matter and 513,000,000 tons of suspended matter are annually removed to tide water by the rivers of the United States (Dole and Stabler). The average weight of the surface rocks of continents is less than 170 pounds per cubic foot. Granites among igneous rocks and limestones among sedimentary rocks each average about 170 pounds; the other sedimentary rocks are lighter. There is thus removed from the United States each year enough rock material to produce 9,211,765,000 cubic feet of solid rock,

that is, $$\frac{[270{,}000{,}000 + 513{,}000{,}000] \times 2000}{170}.$$

Since the area of the United States is some 3,000,000 square miles, it would require over 9000 years to remove what would average a foot of solid rock from its entire surface,

that is, $$\frac{5280^2 \times 3{,}000{,}000 \times 1}{9{,}211{,}765{,}000}.$$

Most of this is, of course, eroded from the high lands. To lower the average height by 1000 feet, thus reducing the lower lands to broad plains, would require at this rate 9,000,000 years. Naturally, however, at the present stage of exceptionally high lands and enormous beds of unconsolidated rock, erosion is exceptionally rapid. Gradually, as the land is made lower through erosion, less and less of the material will be carried in suspension, with the consequence of a very greatly reduced rate of erosion. This would tremendously increase the number of years required for the removal of even the first thousand feet. Hence the *unconformities* (Fig. 77), that are indicative of upheaval and erosion of lands, represent unrecorded periods of unknown, though vast, numbers of years. The nature of the sediment, and of the life, indicates that such high lands as exist today are exceptional in the history of the earth. The usual condition was one of low lands with widespread and shallow oceans embaying the continents; under this condition the rate of erosion and the consequent deposition of sediment would be much slower than it is today, — how much slower it is impossible to say.

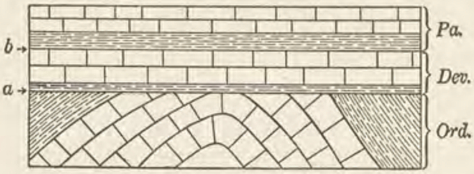

Fig. 77. Time intervals unrecorded by any deposits

Length of section, one mile; all strata marine. At *a* is an unconformity between the Ordovician and the Devonian strata. This records the upheaval of the Ordovician strata into a mountain, its erosion to a plain, and the incoming of the seas in Devonian time. At *b* is a disconformity; the strata above and below are conformable, but those of Mississippian time are missing, as is indicated by the resting of the fossil-bearing Pennsylvanian rocks directly upon those of Devonian age. Strata of the Mississippian either were not deposited here or, if deposited, had been eroded before the deposition of the Pennsylvanian

Thus the stratigraphic breaks (unconformities), the many faunal breaks (disconformities) (Fig. 77), the inconceivable number of slight breaks of comparatively few years, due to decreased rainfall etc., which would be recorded by neither sediment nor life, indicate the vast amount of time that has failed to be recorded in deposits of sediment. Even massive limestone deposits contain numerous horizons full of cross bedding, mud cracks (Fig. 18), ripple marks, and raindrop impressions, — signs of an absence of continuous deposition because of a lack of subsidence. When there is added to this the much slower rate of erosion and consequent deposition throughout most of the past, it is clear that the age of the earth cannot be even approximated correctly by the method of erosion and deposition.

Measurements of time based on radioactivity. In radioactivity, transformations take place only from an element of higher to one of lower atomic weight, and no one has been able to alter the rate of this transformation. Uranium, for example, passes through a series of successive stages during its disintegration, which terminate in an isotope of lead, having an atomic weight of a unit less than that of ordinary lead but chemically indistinguishable from it. The order and rate of this disintegration are known with a high degree of accuracy, so that a determination of the amount of the isotope of lead present in the minerals containing uranium makes it possible to determine with some degree of certainty the time when disintegration began. In other words, since an atom of uranium, upon breaking down, gives rise ultimately to eight atoms of helium and one atom of lead as stable products, and since these stable products can be measured and compared with the amount of uranium still present, and since the rate of this change is known, data are obtained for measuring the age of the mineral and thus of the rock containing it. Thus Strutt, one of the earliest workers, found that the thorianite which he used contained 280,000,000 times as much helium as the same mineral could generate in a year, and that consequently it must have taken at least 280,000,000 years to generate it. Apparently all the helium in rocks comes from radioactive substances there present, and since when a mineral is exposed to air, it begins to lose its helium, which is a gas, the amount of helium found to be present upon analysis can be only a part of that generated, and can hence give only a minimum estimate of age. The amount of lead present leads to more definite results, provided the isotope is distinguished from the ordinary lead that may be present in the rocks. Thus it is that many physicists, geologists, and astronomers agree that the age of the earth can be most accurately estimated from the rate of radioactive disintegration. It is a clock which is apparently always active and whose rate of movement does not change (Table III).

TABLE XII. AGE OF THE EARTH IN YEARS ACCORDING TO MEASUREMENTS OF TIME BASED ON RADIOACTIVITY

After Barrell

ERAS	PERIODS	LENGTH OF PERIOD IN MILLIONS OF YEARS	MILLIONS OF YEARS SINCE PERIODS BEGAN
CENOZOIC (55,000,000 years)	Holocene Pleistocene		1
	Pliocene	6	7
	Miocene	12	19
	Oligocene	16	35
	Eocene Paleocene	20	55
MESOZOIC (135,000,000 years)	Upper Cretaceous	40	95
	Lower Cretaceous	25	120
	Jurassic	35	155
	Triassic	35	190
PALEOZOIC (360,000,000 years)	Permian	25	215
	Pennsylvanian	35	250
	Mississippian	50	300
	Devonian	50	350
	Silurian	40	390
	Ordovician	90	480
	Cambrian	70	550
PROTEROZOIC (450,000,000 years)			925
ARCHEOZOIC			1125 1400

NOTE. The pre-Cambrian is not here divided into periods. The time estimates in the last column date in general from the middle of the Proterozoic and from some distance down in the Archeozoic.

TOPICAL REVIEW

- Sediments
  - Stratified deposits
  - Unstratified deposits
  - What sediments tell us
    - Color of sediments very significant
- Fossils
  - Conditions necessary for the preservation of fossils
  - Proportion of plants and animals preserved as fossils
  - What fossils tell us of the once living animal
- Subdivisions of earth history
  - Basis of subdivision
  - Subdivisions
- Age of the earth in years
  - Deposition and erosion method of estimating the age of the earth
  - Measurements of time based on radioactivity

CHAPTER XII

PRE-CAMBRIAN (ARCHEOZOIC, PROTEROZOIC)

ARCHEOZOIC (ARCHEAN)

Underlying all the later sedimentary rocks of the earth is a great basal platform composed of highly contorted, intensely metamorphosed rocks. These rocks are accessible to us at the surface of the earth wherever the region has stood for many ages above the level of the ocean and has thus been subjected to a long-continued erosion, or where a later upheaval of mountains has, through consequent erosion, brought to the surface these deeper-lying beds.

These rocks are largely gneisses and schists, penetrated in many places by granites. They show that the remotest period of earth history was a time of intense folding upon every continent, for gneisses and schists are sedimentary and igneous rocks which have been metamorphosed by pressure and heat (Fig. 78).

Following upon the cosmical history of the earth, when its parent nebula contracted into the sun, and this in turn evolved into the separate planets and our sun, came the individual, or geological, history of the earth. The early earth is conceived by many scientists to have been molten. Gradually the surface cooled sufficiently to form a more or less solid crust overlying the still molten layer immediately beneath. Below this fluid layer and extending to the center were the heavier minerals, acted upon by gravity and forming a solid mass.

Upon this hypothesis of a molten earth, a period of intense igneous activity immediately followed the formation of a solid crust. The cooling of the molten layer, extending to a depth of many miles below this crust and early sediments, would cause the outer part of the earth to be strongly drawn toward the center of the earth. If this contraction continued throughout the Archeozoic, it could conceivably give to the rocks of this era, both igneous and sedimentary, their present characteristically crumpled and contorted appearance.

The period immediately following the formation of a cool crust and the development of winds and rain saw the beginning of the weathering of solid rocks and the transportation and deposition of the rock particles, forming sedimentary beds. Upon the hypothesis that the earth was molten when full-grown, this period would naturally be one of great volcanic action, for the internal liquid lavas would penetrate, break through, and then overflow the old crust and early sediments.

Fig. 78. Idealized east-west section through eastern North America at the beginning of the Paleozoic

The contorted gneisses and schists of the Archeozoic (Archean) are penetrated and partly absorbed by the later granites. The geosyncline (*C*) was apparently due to the downsinking of the heavy sediment beneath the Atlantic Ocean (*A*), with the consequent westward pressure of the Appalachian land mass (*B*). Erosion of this repeatedly elevated land mass throughout the Paleozoic kept the sinking trough (*C*) filled. At the close of the Paleozoic a much greater depression of *A* crumpled up the sediments within the geosyncline into the Appalachian Mountains. *D* is the eastern edge of the more stable interior land mass

The crust was in places sufficiently strong, however, to permit the formation of some deep troughs where sediment accumulated. Such a trough was the Laurentian geosyncline, in eastern North America, extending 1400 miles from Labrador to Lake Superior. A cross section through the southern portion of this trough shows thick limestones (Grenville formation) at the southeast and sandstones and conglomerates at the northwest, evidence that the sediments were derived from the northwest. At the close of the Archeozoic the accumulated material was thrown into northeast-southwest-trending mountains. The thrusting force came from the southeast, due apparently to the downsinking of the embryonic North Atlantic

Ocean basin. This is one of the earliest evidences that the development of this basin had begun.

In North America Archeozoic rocks have their widest surface distribution in the northeast,— from Lake Superior north and northeast through Labrador and Greenland. In Europe they are widespread in the northwest, especially in Finland and Scandinavia. In both continents the younger strata dip away from these old lands. Most of western Australia is Archeozoic in age, as is also most of Africa and northeastern South America

PROTEROZOIC (ALGONKIAN)

It is conceived that, as the ages passed, the earth fires so characteristic of the Archeozoic gradually lost their fervor, and the earth became solid from center to circumference (except for the temporary and local development of molten magmas). Thus the sedimentary rocks were subjected in a greatly lessened degree to baking and contorting effects.

The rocks of the Proterozoic differ profoundly from those developed during the preceding Archeozoic era. They imply in their more mature weathering and subsequent deposition the presence of the same agents that are now operative. Sandstone and shale are an evidence that the solid rocks were being weathered then as now, that the rain falling upon the lands washed the products of rock decay into lower-lying basins, where, as their stratified appearance shows, they were laid down in water. Evidence of currents, probably due to rivers, is frequently present in the form of cross bedding and ripple marks. Yearly changes in climate from wet to dry are recorded in the widespread development of red beds. Most of these sediments were probably laid down not in the ocean but upon the continents, either by streams overflowing their banks at times of high water or as deposits in lakes. Such continental origin is shown by the fact that very many of the sedimentary rocks are red beds and that others show among their few fossils an almost complete absence of undoubted marine forms and the presence of fresh-water forms. The sudden appearance of vast numbers of marine animals in the basal Paleozoic beds can likewise be best explained on the hypothesis that substantially all Proterozoic sediments are nonmarine (p. 186).

Sediments of this era are abundant upon all the old lands of the earth, that is, upon lands that for many geological ages have been above the level of ocean waters and hence subject to erosion. Their distribution is very similar to those of the Archeozoic. In North America they occur in eastern Canada and as the core of old mountains. In Montana and British Columbia there are 37,000 feet of sandstones, shales, and limestone, known as the Belt Series, that were deposited during the Proterozoic era. Near the base of the Grand Canyon of the Colorado in northwestern Arizona the river has cut through beds of this age. There remain, in this locality, after the tremendous erosion that took place during the earliest Paleozoic, 12,000 feet of sandstone, shale, and limestone. In Ontario there are 20,000 feet of lower Proterozoic (Sudburian) white sandstone, now metamorphosed into quartzite. During the Proterozoic also there were deposited, and then weathered to a point of economic importance, the great iron-bearing beds (Animikean, etc.) of the Lake Superior district (see page 156). At the close of this era, and possibly extending into the basal Paleozoic, there accumulated in the Lake Superior region 15,000 feet of sandstones (Keweenawan). This was followed by the outpouring of some 35,000 feet of lava flows, mostly basalts. This igneous upwelling was accompanied by waters rich in copper and silver. The copper is largely native, giving the most extensive deposit of pure copper known; it occurs as a cement between the pebbles of the sediment and in pores and cracks of the igneous rocks. At the same time, apparently, an igneous upwelling with waters rich in copper, silver, and nickel penetrated the Sudburian rocks of Ontario (at Sudbury etc.), giving to them rich ores of these metals. At the close of Proterozoic time mountains were developed (as in the Grand Canyon region of Arizona) and plateau-like uplifts were formed.

Proterozoic glaciation. Evidence of the existence of glaciers in this remote period of earth history is undoubted and widespread. The earliest evidence of this kind is from North America. In Ontario and Quebec, still resting in places beneath upper Proterozoic sediments, there occurs an unstratified clay (now converted into slate) containing scattered, usually subangular bowlders, some of which are blocks weighing tons. Bowlders are crowded together or sparsely scattered through the slate. Many of the bowlders have faceted edges and striated surfaces, as though in the grip of the moving ice they had been scraped against the rock floor. The old rolling, rock-floored lands, still grooved and polished, are exposed in several places. In places also occur bands of stratified rock apparently deposited by the water from the melting glacier. These glacial deposits are known to have an extension of 1000 miles from east to west and of 750 miles from north to south. There is thus evidence that even during these very early days of earth history a glacier of continental proportions existed in North America. Advancing probably from the north and continuing south at least as far as the north side of Lake Huron (lat. 46°), it plowed over the rolling lands, planing off the soil and weathered rock and then grooving and polishing the solid rock beneath. Upon the return of warmer times the ice gradually melted back, leaving the bowlders, sand, and mud where they happened to fall (Coleman).

In many other parts of the earth evidence of the presence of glaciers during Proterozoic time is constantly accumulating. In southern Australia, Tasmania, and northern Norway glaciers developed at the close of the Proterozoic, as the deposits due to them rest directly beneath fossil-bearing beds of the basal Paleozoic (lower Cambrian). In Australia deposits consisting of angular and rounded bowlders scattered through unstratified clay (now slate) reach a thickness of 1500 feet. In other regions glaciers are known to have occurred at some time during the Proterozoic. Since fossils are exceedingly rare in Proterozoic sediments, it is very difficult to date events with any degree of accuracy. Glaciation occurring at some time during the Proterozoic is recorded from South Africa, India, the middle Yangtze River region (long. 110° E., lat. 31° N.), northern Scotland (where the deposits rest upon a glaciated floor at the base of a 14,000-foot sandstone (Torridonian) of terrestrial origin), and the Lake Superior district of North America.

LIFE DURING THE PRE-CAMBRIAN

Archeozoic. That life made its first appearance upon earth rather early in the Archeozoic, when it began its long upward climb, is undoubted. The vast amount of carbon in the sedimentary rocks of this time indicates that organisms were abundant. Carbon today is derived from the carbon dioxide of the air through the action of plants. Every line of evidence indicates that it had a similar origin yesterday and each preceding yesterday back into the Proterozoic. Wherever present,— in coal beds, in black shales, in oil deposits,— carbon is always associated with plant or animal life. Hence the presumption is unavoidable that the carbon in the still earlier Archeozoic had a similar origin.

It is estimated that the 50,000 feet of Grenville limestone of Ontario, Archeozoic in age, contains as much carbon as there is in the Carboniferous coal beds of Pennsylvania; this carbon is now in the state of graphite. Quartz schists rich in graphite are abundant in the Archeozoic throughout the world. In the Adirondack Mountains of New York there are alternating beds of graphitic schists from three to thirteen feet thick, looking like fossil coal beds.

Aside from possible microscopic blue-green algæ preserved in the chert in Minnesota, described by Gruner, and the Eozoön (doubtfully also an alga) from the Grenville limestone of Ontario, described by Dawson, nothing is known indicating the kind or shape of the organisms then living; but, judging from the fossils of the Proterozoic, as well as from the evolution of plants and animals during succeeding eras and from the embryology of living forms, the organic life probably consisted largely of the plant-animal and the one-celled plant types, living principally upon the inorganic substances in solution in the waters. Upon their death they would mingle with the accumulating sediment, giving rise after metamorphism to graphitic schists. In bodies of water where no muds or sands were being deposited they might react upon the lime in solution; for, with the absence of active hunters and scavengers on the floor of the water body, as implied in these postulated lowly forms of life, the ammonia given off by the partial decay of the organisms would precipitate the lime salts (Daly). This may have been the origin of such limestones as those of the Grenville, while the undecomposed remnants of carbon might become the graphite of today.

Proterozoic. While thus for Archeozoic time the evidence of the kinds of organisms then living is confined to that of possible blue-green algæ, in the Proterozoic undoubted fossils are in places abundant. Throughout thousands of feet of sediment of this age limestones abound in calcareous secretions of the blue-green algæ, up to a foot or more in diameter. Gruner has found microscopic blue-green algæ and bacteria in Minnesota. In the Grand Canyon region of Arizona many siliceous sponge spicules have been found and also large, cabbage-like secretions (Cryptozoön etc.) of the blue-green algæ, forming thick limestone masses. Similar forms are present in the Belt formation of Montana and British Columbia, while bacteria are inclosed by some of the algæ (Walcott). Later in the Proterozoic, from the upper part of the Belt formation, are found worm burrows and possibly mollusk trails, as described by Walcott.

Thus, while the known plants are confined to the two lowest groups, the bacteria and blue-green algæ, the close of the Proterozoic saw among animals representatives of protozoöns, sponges, and worms. Through the later-known evolution and the embryology of these groups their presence implies also the presence of at least the cœlenterates. That the other phyla of the invertebrates were likewise present is indicated by their well-developed condition at the beginning of the next era, the Paleozoic.

That life was very abundant during the Proterozoic is evidenced by the great amount of carbon in the dark sediments throughout the world. It has been estimated, for example, that the amount in the dark shales of the Animikean formation extending from Michigan, Wisconsin, and Minnesota into Canada would, if concentrated, make a bed of anthracite 200 feet thick.

The interpretation of these early life forms as nonmarine is borne out by the red character of so many of the sediments. If this is so, we may picture the various continents during the Proterozoic as much larger than at present and bordered upon their margins by high mountains (Walcott), mountains that have since been depressed beneath the ocean waters by the continual downsinking and lateral spreading of the ocean basins.

TOPICAL REVIEW

- Archeozoic (Archean)
- Proterozoic (Algonkian)
  - Proterozoic glaciation
- Life during the pre-Cambrian
  - Archeozoic
  - Proterozoic

CHAPTER XIII

PALEOZOIC

With the beginning of the Paleozoic era, life had become so well established, and had differentiated into so many forms, that there is usually no difficulty in distinguishing the deposits in which they occur as of marine or of fresh-water origin. Hence from this time onward it is possible to determine something of the continuously changing geography of the earth. The most noteworthy characteristic of earth history as thus recorded in the sediments and their included fossils was the frequent alternation of times of widespread marine inundation of the lower-lying lands of all continents with times of a broad withdrawal of these waters. This succession is expressed in the alternation of widespread marine beds either with terrestrial strata or with an entire absence of deposit. Such alternation is apparently associated with the deepening of the ocean basins through the agency of the contracting forces within the earth (see page 127). When the forces become sufficiently great to overcome the resistance of the matter beneath and at the sides of an ocean basin, a deepening occurs, with the consequent drawing into it of the shallow waters resting upon all the continents. During the time immediately following such withdrawal of ocean waters, erosion and the development of fresh-water deposits would be widespread. At the same time, however, the great amount of sediment deposited in the ocean because of the higher continents and the soft character of so much of the newly elevated land, aided possibly by the subsidence of some lands which may temporarily have been shoved above a permanent position of equilibrium, would again raise the ocean level, with a consequent gradual resubmergence of the lower lands of the earth. In these broad bodies of shallow ocean waters lime-secreting animals and plants would quickly abound, forming widespread marine limestones. This alternation of deposits has naturally formed the basis, in a general way, for the subdivision of the eras of earth history into periods.

CAMBRIAN

All known continents were land areas subject to deep weathering and erosion during the latest Proterozoic. Accordingly the first deposits laid down in the encroaching seas of early Cambrian time were the residual sands that were reworked by the sea (Fig. 79). Accompanying these sands was the material eroded from the rocks newly disintegrated. Some of the resultant muds are represented by slates, such as those of New York and Vermont.

Fig. 79. View showing an uneroded remnant of Paleozoic rocks resting upon the pre-Cambrian Pikes Peak granite, Perry Park, Colorado

The cliff shows Cambrian (Sawatch) white sandstone at the base resting upon the pre-Cambrian granite, followed above by the Mississippian (Millsap) thin-bedded limestone and capped by the white Pennsylvanian Fountain formation. The granite batholith was intruded into pre-Cambrian rocks late in the Proterozoic time. The region was then elevated and eroded so as to expose the coarse-grained granite before the incursion of ocean waters in late Cambrian times. The Mississippian beds rest immediately upon the Cambrian with similar dip; they are hence disconformable to them, for a long time element is missing (Fig. 77). (Photograph by G. B. Richardson. Courtesy of the United States Geological Survey)

In North America at the beginning of the Cambrian the higher and more unstable lands of Cascadia and Appalachia (Figs. 78, 80), bordering the present continent at the west and east, were, it is supposed, thrust away from their respective oceans, and mountains developed bordering the oceans and reciprocal troughs where the inner sides of the highlands bordered the more stable interior lowlands. Into these troughs — the Paleocordilleran and Appalachian geosynclines — came extensions from the Pacific and Atlantic oceans. These geosynclines continued, throughout the Paleozoic, to be the principal zones of accumulation of sediment. Into these catchment basins the streams carried the residual sands from the reëlevated lands of Cascadia and Appalachia. Apparently the interior lowland was too low to have its eroded sands thus removed, since the sediments increase in coarseness away from it. Partly because of the sediment poured into the various oceans, the seas had gradually overflowed the troughs by mid-Cambrian time, flooding parts of the interior lowlands, and

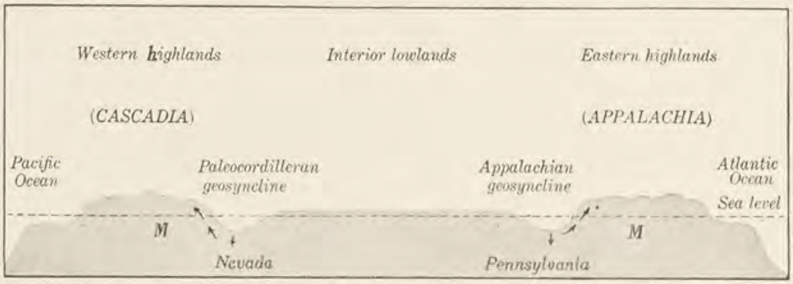

Fig. 80. Generalized east-west cross section of North America during the Paleozoic

The present margins of the Pacific and the Atlantic oceans are at *M*. The extent to which the ancient highlands of Cascadia and Appalachia reached beyond the present margins of the continent is unknown. These highlands were bordered upon their inner sides by geosynclines in which accumulated the thickest deposits of Paleozoic sediments known in North America. A lowland plain extending from the Arctic Ocean to southern United States occupied the medial portion of the continent. This was at times covered by shallow ocean waters, as shown by the thin, mostly calcareous deposits. The arrows indicate the direction of the movement of the material deep within the earth to maintain isostatic equilibrium during the deposition of thousands of feet of sediment in the geosynclines had extended still farther in the upper Cambrian. (An erosion to sea level of the continents today would raise the ocean level 650 feet (George), an elevation sufficient to submerge again the median portion of North America.) Naturally the earliest deposits throughout the interior lowlands were the reworked residual sands, while upon these were deposited limestones, either organically or inorganically precipitated, since the lands were too distant to furnish much mud or sand to this region.

Similarly in other continents, as has been determined in Europe and Asia, the ocean in early Cambrian time, creeping over the land, gradually spread, with one or more partial retreats, to a maximum in the upper Cambrian, when widespread limestones, inclosing many marine fossils, were deposited.

The close of the Cambrian appears to have been accompanied by an uplift of the northern lands (northern Scandinavia and the region from central New England to northern New Brunswick). According to some geologists the uplift was accompanied by a complete withdrawal of the ocean waters from North America and Europe; according to others the upper Cambrian seas continued in many regions to expand into the Ordovician.

Abrupt appearance of fossils at the beginning of the Cambrian period. Although the great amount of carbon in the Archeozoic and Proterozoic rocks is evidence that abundant life must have existed during those eras, yet the remains of fossils are exceedingly rare. Even in the Proterozoic, fossils are practically confined among plants to lime-secreting algæ and to protozoöns, sponges, and annelid worms among animals. In the lower Cambrian, on the other hand, fossils are very numerous, representatives of all existing phyla except land plants and backboned animals being present. Naturally all are very primitive representatives of their phyla. Among the stalked echinoderms only the most primitive cystoids are present. The gastropods have usually simple cup-shaped shells. Most of the brachiopods are of the hingeless types with little lime in the shell. By far the most abundant forms are the trilobites, the most primitive of all known crustaceans. Similarly, among plants representatives of only the lowest division, the thallophytes, occur; these are usually algæ of various types.

The presence during the Proterozoic of such highly evolved animals as annelid worms indicates that most phyla were already in existence at this early time. But since it is probable that no marine sediments of Proterozoic age are known, all known continents must have extended beyond their present boundaries. Hence only a few of such forms as lived in the fresh land waters are known to us. The marine organisms that must have flourished in the shallow epicontinental seas, living their lives and evolving into new forms during these early days of earth history, are unknown; but it is obvious that during this long period various new forms of marine animals must have evolved, many of which developed hard skeletal or protecting parts, so that when the downwarping of various lands at the beginning of the Paleozoic permitted the seas to invade our present continental area, they were accompanied by a great variety of animals whose hardened external skeletons permitted their preservation. In plants, except among those comparatively few groups which secreted lime or silica, the possibility of preservation was exceedingly remote until the development of woody fiber by the ferns in the much later Devonian time, and through these its continuance in all higher orders. (For physical conditions during the Cambrian see page 162.)

ORDOVICIAN

During the Ordovician the continents became increasingly submerged (with two or three withdrawals and readvances up to their maximum in mid-Ordovician (Trenton) times, when more than half of the present land area of North America was covered), and consequently there was a widespread deposit of limestone. The submergence was greater than that of the Cambrian, for in many places basal Ordovician sandstones rest directly upon pre-Cambrian rocks, as in the Arctic islands west of Greenland; in this area the mid-Ordovician (Trenton) rests unconformably upon the pre-Cambrian and, followed disconformably by lower Silurian (Niagara) strata, dips gently northward beneath the Arctic Ocean. Of the marine fauna flourishing in the Arctic Ocean at this (Trenton) time, more than half was present likewise in the continuation of the sea southward across the United States, indicating a uniform climate over this extended area.

Life of mid-Ordovician times. If, going back into the past, we could live for a time upon the eastern margin of this great interior sea (for example, in what is now central Massachusetts), we should be amazed at the strangeness of our organic environment. Although physical forces have remained substantially unchanged throughout the intervening millions of years, the world in which they then operated would be unknown to us. The sun rose and set, bringing the accompanying day and night, and twice during this time the tide rose and fell. At night the moon shone brightly and the stars, doubtless with a different grouping, sparkled brilliantly. At times fleecy white clouds drifted slowly across the blue sky; at other times dark storm clouds scudded before the wind, bringing the pelting rain. From beneath a cliff not far away a cool spring flowed, gradually merging its waters with those of a larger stream, which, flowing down through a valley upon the western slopes of the eastern continent (Appalachia), poured into the ocean near us; while far to the west, where is now eastern New York, an ocean current was sweeping south and west (Fig. 81).

Gradually, however, while noting the great similarity of the physical forces at work during the Ordovician times to those of today, we become aware that the world is, after all, a very strange one. Aside from minute algæ upon the more moist soil and rocks, and the flat expansions of liverworts along the edges of streams and in swamps, we see absolutely no signs of life on land. (For the probable presence of liverworts at this time see page 309.) There are no trees, bushes, or grass. There are no birds and no insects. No animals, large or small, are roaming the upland or scurrying among the rocks. We are gradually impressed by the fact that neither land nor air has as yet been conquered by animal life or by any but the lowest forms of plant life.

In the streams, however (at least in their lower reaches, where they merge with the ocean waters), we catch sight of two kinds of strange animals,— animals that remind us somewhat of the horseshoe crab so common today in the protected harbors of eastern North America, grubbing in the mud of our modern Atlantic Ocean. One group of these, the eurypterids (Fig. 125), which seem to be rather closely related to our horseshoe crab, have one pair of legs developed into broad and strong paddles with which they swim and burrow in the mud. The other group of these strange animals are the shield fish (ostracoderms), of unknown affinities. These last bizarre animals are also mud-grubbers, with a shield covering the head and anterior part of the body, and with a long, flexible tail, but without a trace of a backbone.

Fig. 81. Evidence of current action in eastern New York during the Ordovician

Each light-colored line is the carbonized remnant of a colony of graptolites (cœlenterates allied to the jellyfish). Through hundreds of feet of rock these are arranged in parallel rows always pointing in the same direction for any particular locality. Only a gentle current moving always in the same direction could produce this arrangement. The direction of the graptolites (and hence the direction of this Ordovician ocean current) is south by southwest at Schenectady, southwest at Little Falls, and almost west at Utica, due, according to Ruedemann, to the fact that the ancient Greenland current moved south and west around the Adirondack land mass

Upon turning our attention to the life within the shallow ocean we see that its floor teems with myriads of animals. There are no fish or other backboned forms. In place of these, long torpedo-like shells (orthocerids) shoot through the water slightly above the ocean floor, propelled by jets of water expelled from a tube beneath the head. The head, bearing two large, saucer-shaped eyes, is surrounded by a circle of flexible, ropelike arms with which the animal entwines its food until it can tear it in pieces with its jaws. These are the straight-shelled cephalopods (Fig. 124, *a*). An examination of the forms thrown upon the beach by the waves shows that there are not only straight shells but also curved (Fig. 85) and even closely coiled ones, all chambered like their present-day descendant, the chambered nautilus (Fig. 124, *b*).

Crawling over the bottom or swimming slightly above it are other strange animals which resemble somewhat our modern sowbug; but from head to tail extends a median broad ridge, giving the back a three-lobed appearance. These carnivorous animals are the trilobites (Fig. 125), the earliest crustaceans. That they are a successful development is indicated by the immense number, both of individuals and of species, that crowd the ocean floor. Creeping over the bottom more slowly are starfish and many shelled forms which we recognize as marine snails, while partly buried in the mud are animals resembling our modern mussels. By far the most abundant shelled animals upon the ocean floor are the brachiopods (Fig. 122). These two-valved forms, usually less than an inch in length, were supremely successful in the Ordovician seas, judging from the number of individuals and the variety of forms present in the Ordovician strata accessible to us today. They have, however, been unable to withstand the competition of later forms, for very few brachiopods survive in our modern world. In waters freer from sediment because farther from shore we see, fastened to the bottom, many corals, both individual cups and compound reef-building ones. With these are crinoids (Fig. 85); these are plantlike in having a slender stalk fastening the small cup with its crown of branching arms to the bottom, but they live entirely upon organic food.

This is a very strange world to which we look back in the Ordovician, with its familiar physical forces which were to operate unchanged through the millions of years since passed, but with a plant and animal life so lacking in familiar forms. Yet the various organisms in the Ordovician give evidence that they were evolved by the same forces which, continued from that time to the present, have given rise to the more varied assemblage of our modern world. Although the individuals were strange, the ground plan was the same in the Ordovician as for the primitive forms living today.

Mountain-building. Gradually, during the upper Ordovician, the seas began to recede, until, with one or two temporary readvances, they were withdrawn almost completely from the present continents.

The depression of the ocean basins that drew the oceans from the interior of the continents brought sufficient pressure against the land to crumple the weaker portions,— the water-laden and unconsolidated beds of the deeper geosynclines. In consequence folded mountains were developed; apparently this took place in the areas where deposition had been most rapid, that is, in eastern North America (the Hudson River valley and extending possibly to Nova Scotia) and in western Europe (Wales, western England, and Scotland), for in these areas Silurian beds are seen resting unconformably upon upper Ordovician rocks (Fig. 82), while east of this region in Europe (as in Gotland and Finland) and west of it in North America (as in the Mississippi Valley) the Ordovician and Silurian strata are conformable. (The accumulation of Ordovician sediments in Wales and northwestern England was accompanied by vast outpourings of lava and volcanic ash.) This enlargement of continental area was naturally accompanied by an increase in the extension of aridity and in certain regions by interior basins. Where these two conditions joined, as in the Irkutsk geosyncline in Siberia, gypsum and rock salt accumulated.

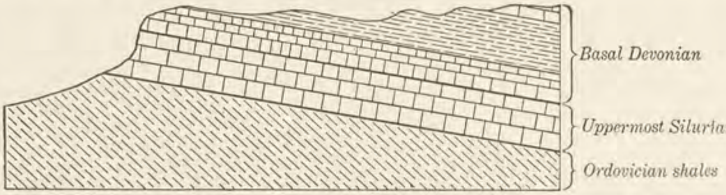

Fig. 82. Section at Becraft Mountain, Columbia County, eastern New York

The Ordovician shales dip about 40° E., the Silurian and Devonian limestones and shales about 10° E.; hence there is an unconformity between the two. All beds are fossil-bearing and marine

SILURIAN

Because of the sediment poured into the seas from the eroding lands, accompanied by the partial slumping of the continental areas into the oceanic depressions and by the increase in oceanic waters from vulcanism, the seas again began to creep slowly in over the lower-lying portions of the continents (Fig. 83) until, by the close of lower Silurian (Niagara, Wenlock) time, nearly half of North America was submerged and also large parts of Europe, Asia, Australia, and South America. With broad, shallow seas it was hence a time of widespread deposition of limestone. It was similarly, at least for the entire Northern Hemisphere, a time of warm temperate or even possibly subtropical climate, as the same fauna of reef-building corals and many other marine animals abounded in the continuous seas covering central North America north across the Arctic islands and thence south into Europe and Asia.

Fig. 83. North-south section through New York State

This extends from the Pennsylvania-New York State line through Niagara Falls (at Niagara escarpment) to the Laurentian plateau in Canada. (Courtesy of the United States Geological Survey)

This period of crustal quiet was apparently followed by earth contraction, bringing about a depression of some ocean basin, with the consequent withdrawal into it of the water of the majority of the continental embayments and marginal seas. During this mid-Silurian (Salina) time of broad lands a humid climate caused erosion throughout Europe, while in eastern North America (New York, Ohio, Ontario, Michigan) aridity gave rise to widespread and thick deposits of rock salt. At intervals in this desert region a slightly increased rainfall caused the deposition of mud in which were buried many fresh-water fish and mud-grubbing eurypterids (Fig. 125). At Ithaca, New York, there are seven alternations of shale and salt, each of the fourteen beds averaging thirty-five feet in thickness.

During the upper Silurian (Monroe of North America, Ludlow of Europe) the continents were again broadly submerged. In the Appalachian region this submergence continued into the Devonian.

Mountain-building. Toward the close of the Silurian a period of depression of the ocean basins again drew into them the waters of the continental embayments and caused sufficient lateral pressure to bring about, during the uppermost Silurian and lower Devonian, a northeast-southwest crumpling of surface rocks in northwestern Europe and an east-west one in the Irkutsk region of Siberia. The foldings in Europe, known as the Caledonian Mountains, extended from Spitzbergen through Scotland, England, Ireland, and France, causing in the Scottish Highlands and western Scandinavia great overthrust faults, accompanied by volcanoes and deposits of volcanic ash and lava flows. At their maximum these mountains are thought to have exceeded the Alps in height and extent, and yet, so long are geologic periods, by the close of the Devonian "falling drops of rain" had reduced them to a rolling plain and during the Mississippian the ocean waters covered the truncated roots of many of them.

DEVONIAN

Continental deposits (Old Red Sandstone) and life. From the mountains that were being eroded throughout the uppermost Silurian and Devonian times much material was deposited as alluvial fans between the separate ranges,— a process similar to that now taking place in the San Joaquin-Sacramento valley of California between the Sierra Nevada Mountains and the Coast Range. As the yellowish California deposits upon land would become red if exposed to sufficient pressure and consequent heat to drive off some of the water, so the ancient terrestrial deposits of similar origin are now red (Old Red Sandstone). (Where the sediment accumulated in lakes, the carbon was not removed through oxidation, and accordingly the deposits have remained dark or gray in color.) Such intermontane deposits occur in various places in England, Wales, Ireland, Scotland, the Orkney Islands, and Spitzbergen. Deposits of

Old Red Sandstone, probably representing terrestrial accumulations upon the seaward side of the mountains, are known in western Russia and north of Oslo (Christiania), Norway.

Upon the banks of the streams and the small lakes abounding in these regions lived primitive ferns and sedges (Calamites) and probably liverworts, while upon the bottom of the lakes and streams flourished algæ and water ferns. Grubbing through the mud and sand for any organic matter they could devour were many eurypterids and ostracoderms. Many Unio-like pelecypods (Amnigenia) rested upon the bottom, while about them swam great numbers of phyllopod and ostracode crustaceans. There were many kinds of fish, both herbivorous and carnivorous, including lungfish and crossopterygians,— the group of fish ancestral to the amphibians, remarkable for the central fleshy lobe of the fins (Fig. 128) and for the possession of a primitive lung in addition to the gills. During very dry summers some of the ponds dried up, killing off the vast majority of these organisms; and in those rare cases where a very heavy rainfall would bring upon them a thick deposit of mud and sand before their complete decay, they were preserved as fossils. Many such highly fossiliferous gray beds occur in the midst of the typical red sandstones.

Marine deposits and life. While such scenes were taking place upon the higher lands the ocean waters were again creeping in upon the various lowlands of the earth, until nearly half of the present continent of North America was beneath the sea, and throughout the remainder of the earth much of what is today land was similarly covered by ocean water. (It is essential to recall that throughout the Paleozoic the continents probably extended far beyond their present margins, and that from that time they have gradually contracted to their present limits.) This was one of the great submergences known in earth history. During the mid-Devonian the ocean waters extended across mid-Europe and Asia and thence through the Arctic Ocean south across medial North America, with consequent similar faunas.

Upon the floors of these shallow marine basins lived immense numbers of corals, both simple cups and huge reef-building colonies (Fig. 84) ; fastened to the bottom were myriads of stalked blastoids and crinoids, forming widespread miniature forests; and everywhere lay scattered immense numbers of brachiopods. Since death rapidly followed life in these short-lived forms, their calcareous skeletons formed extensive deposits, which during the mid-Devonian alone often reached a thousand feet and more in thickness. In these Devonian seas (Fig. 85) were also many cephalopods, trilobites, and primitive sharks.

Fig. 84. A portion of the ocean floor in Indiana during the Devonian

Upon the lime mud of this ancient sea bottom lived many cup corals, some brachiopods, and a honeycomb coral ("fossil wasp nest"). After the death of these individuals their skeletons were gradually covered by the drifting muds

The Devonian seas which covered much of Europe extended southward into the northern part of the Sahara, as is indicated by the similarity of the marine animals over that area. In Cape Colony, however, the only other part of Africa to be submerged, the marine life was closely related to that living in the seas covering the medial and eastern portion of South

America,— Falkland Islands, Argentina, Bolivia, and Brazil,— giving evidence of a strand line uniting these two continents, along which the brachiopods, pelecypods, gastropods, etc. could migrate, this strand land being the southern edge of a hypothetical land mass called Gondwana (see page 288).

Mountain-building during the Devonian. Beginning in the mid-Devonian and continuing to its close, the land mass of the maritime provinces of Canada was elevated and folded, for Mississippian and Pennsylvanian strata rest unconformably upon the truncated folds of older formations. The elevation was accompanied by the extrusion of lavas and the intrusion of granite. (At this time probably was formed the volcano the eroded remnant of which is now Mount Royal, which gives its name to the city of Montreal.) There was likewise great volcanic activity in Great Britain, France, and western Germany during both the lower and upper Devonian. While New England and southeastern Canada were being uplifted the increased

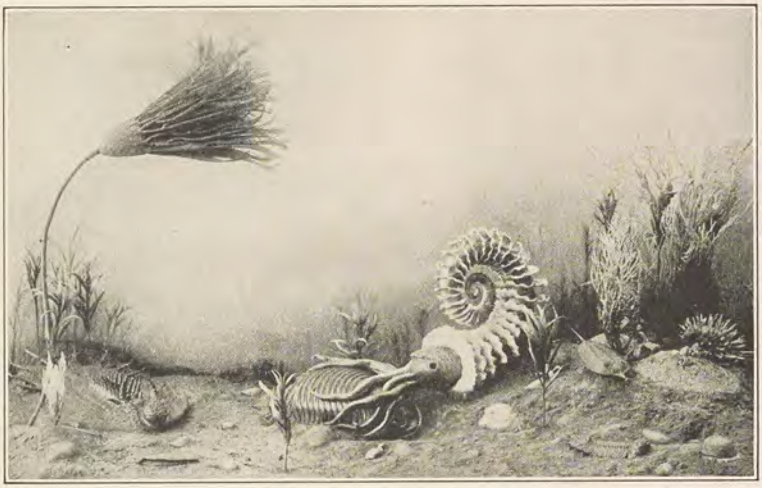

Fig. 85. Restoration of the marine life of the early Devonian

At the left is the crinoid Scytalocrinus, beneath it the spinose trilobite Terataspis. In the center the cephalopod Rhyticeras is feeding on the trilobite Homalonotus. To the right are two other trilobites. In the background are seaweeds. (Courtesy of the New York State Museum) terrestrial sediments deposited upon their western flanks were extended farther and farther westward, over the marine sediments, forming such red beds (Old Red Sandstone) as the Catskill formation of southeastern New York, where today they constitute the main mass of the Catskill Mountains. Since that time the ocean has been almost entirely excluded from the northern Appalachian and New England region. Thus in eastern North America the upper Devonian is separated from the lower Devonian by a physical break. This is also true in the Caledonian Mountains on the opposite side of the North Atlantic land mass. In the latter region the change seems to be expressed only in the character of the sediment; the upper Old Red contains more conglomerate than the much thicker lower portion, with bowlders up to eight feet in diameter (these may represent glacial deposits from local highlands but are more probably torrential deposits). This elevation of the lands of northeastern North America and northwestern Europe was apparently due to a depression of the North Atlantic Ocean basin.

MISSISSIPPIAN

Though the continental area of the earth was considerably enlarged at the close of the Devonian period, inlets from the ocean still persisted in many areas, as into Belgium and northern France, forming a transition between the Devonian and the Mississippian. The Mississippian opened with a widespread incursion of ocean waters during what is known in North America as the Kinderhook stage (Fig. 86). In western Europe it covered the truncated edges of the Caledonian Mountains and extended east through Belgium and northern France into central and southern Russia and the Ural geosyncline. North and south of this European sea were low-lying shores, upon which, now beneath the ocean waters and now above them, accumulated a series of sandstones, conglomerates, and shales, inclosing many land plants. These shore deposits are known as the Culm. In places they seem to have accumulated throughout the entire Mississippian time. Similar Culm deposits are found in Argentina and eastern Australia.

In the mid-Mississippian there occurred a rather widespread withdrawal of ocean waters, during which Europe was characterized by the development of coal beds, usually thin and intercalated with terrestrial sediments, while for North America it was a period of erosion; this indicated for both regions a moist climate. This was for Russia the most important coal-producing time. Thick beds of coal accumulated over widespread regions, as in the Moscow basin of central Russia and the Donetz basin of southern Russia.

Fig. 86. Steep upturn in the rocks of the Front Range of the Bighorn Mountains west of Buffalo, Wyoming

The beds in the middle and at the right are marine, of Pennsylvanian age. The massive limestones of the Madison formation shown to the left and in the high peak are also marine but of Mississippian age (Kinderhook). (Photograph by N. H. Darton. Courtesy of the United States Geological Survey)

During the upper Mississippian a more extended submergence took place, during which median and western North America and northwestern Europe were under water; and a huge Mediterranean sea covered southern Europe, extending thence across central Asia (north of the Tien Shan Mountains) and northern China. These waters were characterized in the three continents by a similar brachiopod fauna, the *Productus giganteus* fauna.

During the Mississippian occurred the climax in the development of the gregarious stalked echinoderms,— the crinoids and blastoids. Frequently they were so numerous that their calcareous skeletons form beds of limestone hundreds of feet thick, almost to the exclusion of any other material.

PENNSYLVANIAN

Following a rather widespread withdrawal of the ocean waters from the continental areas at the close of the Mississippian, the sea gradually crept in over the lower-lying lands to a maximum extent in early Pennsylvanian time, when it was again gradually and rather broadly withdrawn.

North America. Sediment accumulated principally in two broad basins separated by the Rocky Mountain protaxis,— a long peninsula where are now the Rocky Mountains extending southward from a north Canadian continental mass. West of this protaxis the sea occupied portions of the Cordilleran geosyncline, as well as broad areas in California and in Alaska; east of it there occurred repeated alternations of ocean waters and fresh-water swamps.

From Pennsylvania to Oklahoma the seas oscillated back and forth during the early Pennsylvanian, with a consequent alternation of nonmarine and marine sediments. Such broad oscillations indicate very flat lands and consequently the existence of vast swamps during the nonmarine stage, with widespread carbonaceous deposits. In northern Illinois there is evidence that the sea came in and withdrew nineteen distinct times, and alternating with these submergences there developed seventeen successive coal-making swamps. Of the 1500 feet of sediment recording these oscillations one half consists of sandstones. The fossil-bearing marine beds — limestone and shale — vary in thickness from one to twenty-five feet; the coal beds, from six inches to nine feet. Eastward to Pennsylvania, that is, toward the permanent land, the coal beds increase in thickness, indicating fewer marine interruptions of the swamps in these areas. Westward the coal beds decrease until they disappear in Oklahoma and Texas. Between the Rocky Mountain protaxis and the Pacific the Pennsylvanian is represented by marine sediments or by terrestrial deposits without coal; this indicates that the lands of the west were better drained than those of the east.

Life of Pennsylvanian times. In the vast and changing swamps there were numberless large and small islands, as is shown by the gradual change horizontally from coal through carbonaceous shale to sandstone, and finally to absence of deposit. (The Great Dismal Swamp today shows a similar transition from the deposit of carbonaceous matter far within the swamp to the low-lying shore which is subject to erosion.) Upon the margin of the islands and extending out into the more shallow waters of the swamp grew impenetrable bamboo-like thickets of jointed and vertically furrowed plants (Calamites), — ancient fifty-foot relatives of our modern three-foot horsetails (Equisetum) (Fig. 117). Among these plants, but in especial abundance farther inland upon the somewhat firmer soil of the low islands, grew trees, a hundred feet high, with trunks covered with conspicuous leaf scars and crowned with a canopy of long leaves. These were the lordly ancestors of our present-day club mosses, whose tiny trailing branches seldom rise a foot from the ground (Fig. 118). Beneath the uppermost terrace of the forest composed of the club mosses grew tree ferns and seed-bearing ferns (Fig. 72), while the ground was covered with many kinds of the more lowly ferns that we know so well today. In addition to rootlets all these plants had underground stems, which, like our present-day grasses, formed a mat protecting the soil from erosion. They thus tended to give purer deposits of carbonaceous matter to the stretches of open water lying among the various islands.

These somber green forests of slender trunks were without the enlivening colors of flowers or the songs of birds. Neither flowers nor birds had yet appeared upon earth. At times the stillness was broken by the whir of insect wings as a lacy-winged dragon fly passed in search of food. The large size of these insects, some with a two-foot spread of wings, indicates that their food must have been likewise of large size,—very probably some of the numerous cockroaches that infested the damp forests. Both kinds of insects are water-loving forms today. At times a mud-puppy-like form, seven feet long, slowly lumbered up out of the swamp. This was Eryops, one of the largest of the many amphibians inhabiting the swamps. His short legs and heavy, flattened tail show that he was more at home in the water than upon land. Such slow, clumsy, small-brained beasts seem to give little evidence of the great heights to which their descendants would in time attain. With the amphibians and doubtless preying upon them lived reptiles, which were just now beginning to adapt themselves to a more strictly terrestrial life and still closely resembled their amphibian ancestors both in form and in manner of life.

In the open sea beyond the sand dunes which bordered the swamps at the southwest, and in the ocean west of the Rocky Mountain protaxis, lived numerous sharks, at that time the rulers of the open seas. The bottom of the clear, warm waters was crowded with huge numbers of lime-secreting animals. The most numerous of these were corals (some single cups, others growing in huge, reeflike masses), bivalved brachiopods, taking the place of the more highly evolved clams of the modern seas, and especially the simpler echinoderms, fastened to the bottom by long stalks. As the ages passed the remains of these gradually formed masses of limestone hundreds of feet in thickness.

Europe and the Hercynian Mountains. In Europe the Hercynian Mountains, or Paleozoic Alps, began to rise at the close of the Mississippian and continued to be folded at intervals up to their climax in the upper Pennsylvanian. From England east through central Europe, lower Permian red beds rest unconformably upon folded Pennsylvanian and older rocks. The mountains extended as ranges, trending more or less from east to west, from England, through France, Spain, and northern Africa (Morocco, Algeria), and east through central Europe (De Margerie). Of this great mountain system the northwestern arm, known as the Armorican Mountains, extended, as indicated by the strike of the sedimentary rocks, from a vanished land in the North Atlantic east through southern Ireland, southwestern England, Brittany, to south-central France. The eastern ranges, the Variscian Mountains, extended in the form of many parallel ranges northeast and east through central Europe, including the entire region from Belgium south through the Rhine Gorge region of Germany, the Vosges Mountains, and the Black Forest to the region now occupied by the median line of the Swiss Alps, thence eastward through the Thuringian Forest, the Harz Mountains, the Fichtelgebirge, and Bohemia. In some regions, especially in Belgium, the folding was accompanied by much faulting.

North of the Hercynian Mountains the ocean waters, having access from the east, extended as far as England in the uppermost Mississippian, but by means of filling and uplift they were gradually shoved farther and farther eastward until the strand line lay in western Russia; for marine intercalations occur successively in the Pennsylvanian deposits from England toward the east. Within this broad northern basin, as well as in the depressions between the embryonic mountain ranges, extensive swamps developed, in which, as the centuries passed, vast deposits of partially decayed plants accumulated, giving rise to the very rich coal beds of northwestern and central Europe,— Great Britain, France, Belgium, and Germany.

During the Pennsylvanian, marine waters covered the greater part of Russia and southeastern Europe, and spread eastward through central and eastern Asia. In China, however, there were many swamps in which great quantities of coal accumulated, while in Russia the Donetz region, raised above the surrounding sea as a low, swampy land mass, became again an area of coal accumulation.

PERMIAN

Europe. During the uppermost Pennsylvanian and lower Permian the Armorican Mountains increased in height, with the resultant gradual disappearance of coal-producing swamps. Central Europe, lying to the north of the zone of descending air currents at about 30°, naturally gets its moisture from the southwest. Hence the reëlevation of the Armorican Mountains was depriving Europe of more and more moisture. It followed that the Permian was for this region a period of aridity, recorded in the accumulation of red beds and rock salt. Farther east, upon the flanks of the rising Ural Mountains, were deposited sandstones and shales, inclosing remains of some of the land and fresh-water organisms living at that time. Lapping against the western foot of these embryonic mountains the Russian sea connected southward with the enlarged Mediterranean (Tethys) (see page 292). Tethys continued eastward, covering the region where now tower the Himalayas, extending thence southward as a bay into the Salt Range of northwestern India, the northern margin of Gondwana.

During the middle Permian the European seas at least were extended, covering with marine sediments the lower Permian red beds of the Austrian Alps and causing normal ocean waters to enter central Europe through the Russian sea, and then extending to eastern England (Magnesian Limestone). Notwithstanding the transgressing seas, aridity continued, for upon the blocking of the entrance in western Russia, possibly through the development of extensive bars, the entrapped waters evaporated, causing the deposition of limestone, gypsum, and rock salt, and, finally, of potassium salts, in the lowest parts of the basin, the region surrounding the present Harz Mountains; these were in turn covered by wind deposits. Again, later in the Permian, the sea entered this region, producing once more the same succession of economically valuable deposits. The result is that this region contains the richest deposits of potassium salts in the world; they are used largely as a soil fertilizer. The deposits in the Harz Mountains region are commonly known as the Stassfurt deposits, from one of the most important places where the potassium salts are mined.

During the later Permian the Russian sea gradually withdrew, as recorded in the change in the accumulating sediment from marine to red continental deposits, inclosing in wetter places land and fresh-water organisms.

North America. During the early Permian the backbone of the embryonic Rocky Mountains separated a marine basin to the east (Kansas etc.) from one to the west (Utah, Arizona, Nevada, and northwest). Within the western basin were laid down important phosphate deposits. In the later Permian the region to the east of this Rocky Mountain protaxis was cut off from the open ocean and developed great salt beds, apparently without association with gypsum.

Eastern North America continued moist and hence contained many swamps, but because the lands were higher than during the Pennsylvanian the resultant coal seams are thin and economically unimportant.

Continental rise and mountain-folding in North America during the upper Paleozoic. In North America, as in Europe, uplift occurred at the close of the Mississippian. This is indicated on the south by the very thick deposits of continental conglomerate and sandstone of lower Pennsylvanian age extending from central Alabama westward through southern Arkansas and Oklahoma and northern Texas, and on the east by the conglomerate and sandstone (Pottsville) deposited in Pennsylvania upon the western foot of Appalachia. The former must have been derived from the reëlevated lands to the south, probably the northern portion of the West Indian land mass; the latter, from an elevation of Appalachia. Uplift in North America was again expressed in the upper Pennsylvanian by the broad withdrawal of the continental seas from central United States, as well as by folding. In New Brunswick the Permian rests unconformably upon the Pennsylvanian (Millstone Grit). As the eastern and western portions of the continent continued rising the marine embayments retreated to the southwest, producing gypsum and salt deposits in Kansas and Oklahoma during the later Pennsylvanian and early Permian, but with the ocean burying remains of its life in western Texas, Arizona, and Mexico. Finally, by later Permian times, the ocean disappeared even from this region.

This rise of the continent was accompanied by the development during the Permian of the Appalachian Mountains, extending from Alabama northeastward to Newfoundland. These mountains do not now die out in eastern Newfoundland, but end suddenly through the later downfaulting of their eastward continuation. Evidence of this eastward continuation beneath the waters of the Atlantic may be traced for at least 700 miles, through the Newfoundland banks, the Laura Ethel, and the Milne banks (the summits of submerged mountains), and the east-west-trending rocky ridge some hundred miles long, 2500 meters below sea level, and rising 1500 meters above the ocean floor. In fact, charts show an almost continuous submarine ridge between Newfoundland and Ireland, indicating that the mountains formerly continued eastward until they almost or completely united with the westward continuation of the Armorican mountains of northwestern Europe. In southwestern Ireland the Armorican folds do not die out but end in faults, indicating similarly a former continuation westward.

Upper Paleozoic glaciation. At the close of the early Permian, and possibly beginning, in certain areas, in the Pennsylvanian, occurred one of the most important glacial periods thus far recognized in the history of the earth. In southern Australia tillite (solidified till) of this age, including large, faceted bowlders, rests upon a polished and striated rock floor. The sediments indicate repeated ice invasions, interrupted by marine incursions and coal beds, showing that the deposits were laid down upon low lands. In India the glacial beds are similar in the possession of faceted bowlders and a striated basement. (The coal of this age is the most important in India.) In southern Africa the same sort of deposits and striated basement is known in numerous localities from Cape Colony through Transvaal and Rhodesia, to Nyasaland, and apparently northward to beyond the equator. In South America, Pennsylvanian or lower Permian tillites are known from southeastern Bolivia (Mather), south-central and southeastern Brazil (São Paulo, Paraná, etc.), northern Uruguay, western Argentina, and the Falkland Islands. In Paraná the tillite is interbedded with fossiliferous marine sediments (Coleman). Local glacial deposits, apparently formed at the same time, are known from the Yukon, eastern Massachusetts (abundant in the neighborhood of Boston), and Prince Edward Island, possibly also from England, France, Germany, the Alps, the Urals, and Afghanistan.

The glaciers seem to have developed to continental size, but most prominently only within or near the present tropics. In eastern Australia (Victoria, New South Wales, Queensland), South Australia, Tasmania, and New Zealand they have left evidences of their presence from 20.5° to 42° south, and in longitude from 137.5° to about 165° east. In India their traces occur from 18° north to 35° north; in Africa, from north of the equator to 33° south. In South America the western front of a huge glacier extended from near the equator to 52° south. Judging from such characteristics as the direction of glacial striæ, the form of rock ridges, the original home of the rock fragments of the tillite, and the change from true tillites to water-laid glacial deposits, the movement of the upper Paleozoic continental glaciers was northward in India, away from the present Indian Ocean; it was northward in southern Australia and Tasmania, away from the present ocean; in Africa it was southward, away from the equator; in South America it was westward, away from the present South Atlantic Ocean. Glacial advances were apparently separated by warm interglacial epochs in Africa and Australia.

Cause of the glaciation. This glaciation cannot be explained by a shifting of the south pole to the Indian Ocean, as this would bring the broad area of glaciation in South America within the tropics. At present the explanation which seems to accord best with the facts and is most favored by geologists is that the glaciers were developed to a continental size upon the ancient continent of Gondwana (see page 288). At this time, Gondwana apparently not only included South America, Africa, and India but was united with Australia and with Antarctica by way of Australia and South America. Such a huge land mass would initiate a change in ocean currents and a great increase in the strength of the upward-moving air currents, which would cause more hail and snow upon the higher lands (see also the solar cyclonic factor, p. 393). In high areas where the precipitation in the form of hail or snow was sufficient it would gradually move down the slopes in all directions in the form of vast glaciers. They flowed over the surrounding plains, depositing the débris gathered in the higher lands. Some were large enough to reach sea level, even in low latitudes, before melting completely away, as in South America and Australia. The vast thicknesses of débris are an indication of the height of the vanished mountains. The tillite in India and Australia attained in places a thickness of 1300 feet, and in Africa a thickness of 1200 feet.

Effects upon plant life. The development of such widespread continental glaciers doubtless was accompanied, as in the Pleistocene, by a general lowering of the temperature of ocean waters, and thus brought about a general refrigeration of the atmosphere of the earth. The refrigeration was naturally greatest upon the high lands of Gondwana, and in response to it there evolved a flora, called from its most common genus, the Glossopteris flora. That this flora was developed in adaptation to a cold temperature is indicated by the prevailingly entire leaf margins and thick skin of the various species comprising it, as well as by their association with glacial deposits. Spreading over the lands beyond the glaciers of Gondwana, they have left their remains in South America, Africa, India, and Australia, giving an added proof that these now widely separated lands formed at that time one continuous land mass. This hardy flora present throughout the southern hemisphere during the lower Permian did not reach Eurasia until mid-Permian times.

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  - Mountain-building
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CHAPTER XIV

MESOZOIC

At the close of the Paleozoic, during the late Permian, the oceans must have retired beyond the present confines of the continents for a very long time, for when next they leave a record of their presence in the early Triassic they inclose an entirely new assemblage of animals. Not only did there fail to survive a single species from the Permian, but nearly all genera are new. In the extent of the faunal changes which characterize it the Paleozoic-Mesozoic transition period is apparently a repetition of the passage from the Proterozoic to the Paleozoic. The diastrophic movements closing the Paleozoic era left the continents of the earth exceptionally high. Hence the characteristic deposits of the Triassic, as of the preceding Permian, are continental red sandstones and shales. Only very gradually did the ocean waters rise to a sufficient height again to cover broadly the lower-lying lands. From this time of least expansion in the Triassic they gradually spread to a maximum in the Upper Cretaceous, though a minor maximum spread of ocean waters in each mid-period was followed by a more or less complete withdrawal at the close of the period. Toward the close of the Mesozoic we begin to recognize more and more modern features. We distinguish many of our present-day rivers, though flowing hundreds of feet above their present beds, and many of the flowering plants have a very familiar appearance. Upon the whole, however, the lands of the Mesozoic world were strange ones, filled with bizarre inhabitants. As the dominant life of the early Paleozoic consisted of invertebrates and that of the later Paleozoic of primitive fish and amphibians, so, progressively, the Mesozoic world was ruled by reptiles. Mighty in bulk but small of brain, they roamed the lands, swam in the waters of river and ocean, and flew in the air.

TRIASSIC

America. *Marine deposits.* In North America the ocean invaded only the western and northern portions of the present continent, expanding broadly in the Alaskan region. The Arctic extended some distance to the south, recording its presence in sediment containing marine fossils in the northern Arctic islands and in northwestern and northeastern Greenland. The western seas, with a width that reached from central California to western Nevada, were apparently bordered on the west as well as on the east by land. They extended through Central America on the south. Similarly, in South America a geosyncline, receiving deposits partly marine and partly continental, covered the present site of the Andes Mountains from north to south.

Continental deposits and the life of the lands. To the east of the seas occupying western North America continental deposits were accumulating, mostly in the form of red sands and clays. At times of heavy rains the torrents washed down from the uplands of the mountains enormous numbers of trees. These trees, stripped of all leaves and even of branches during their tumultuous passage downstream, were deposited in alluvial fans upon the lower arid lands, where they are found as abundant fossils today. One such deposit comprises the National Fossil Forest, at Adamana, Arizona, where occur numerous trunks, some with a length of 100 feet (Fig. 87). Farther east, from Wyoming to Texas, the deposits are, as a rule, thinner and contain gypsum.

Some time after the folding of the Appalachian Mountains a new geosyncline gradually developed parallel with them upon the old land to the east. Into this elongate depression, formed during the upper Triassic and comparable to the great central valley of California today, the streams deposited their burden of bowlders, sand, and mud, making the red beds (Newark formation) of eastern North America.

Roaming over these alluvial flats, whose cross-bedded sediments give evidence of the occasional turbulence of the streams, were great numbers of bipedal and quadrupedal dinosaurs.

They left their footprints upon the ripple-marked and rain-pitted sandy muds, to be later hardened and cracked by the sun's heat and then preserved under a new layer of sediment. The dinosaurs frequenting the valleys (over one hundred species have been noted) were naturally mostly carnivorous, coming in search of the animals that the torrential streams from the bordering uplands had stranded here. At intervals throughout the valleys occurred small lakes, whose waters flashed with the iridescent scales of numerous ganoid fish. Upon the surface of the waters were aquatic insects (a larva of these, one of the earliest known insect larvæ, was found at Turners Falls in Massachusetts). The lake shores were clothed with rushes, ferns, cycads, and pines, through which labyrinthodont amphibians crept or small reptile-like mammals scurried.

Fig. 87. View in the National Fossil Forest, Adamana, Arizona

This shows the largest tree in the petrified forest; only a portion of the tree is exposed and this is over one hundred feet long. Other petrified logs and the coarse sandstone from which they have been weathered (and which formerly extended to a great thickness over all this region) are seen in the background. (Courtesy of the United States Forest Service)

While these sediments, up to a maximum of 20,000 feet, were being laid down an immense amount of igneous material (basalt) repeatedly welled up, to be intruded as sheets or poured out upon the surface. Such igneous rocks now form the Palisades along the Hudson River and Mounts Tom and Holyoke in the Connecticut River valley of Massachusetts. These basalts and sediments have been preserved to our time by the downfaulting of long, narrow blocks, formed partly at the time of the deposition of the sediment and partly at the close of the Triassic. Such graben fault blocks, with their records of the upper Triassic physical conditions and life, occur in Nova Scotia, the Connecticut River valley of western Massachusetts and Connecticut, and along the Atlantic coast from New Jersey to North Carolina.

At the close of the Triassic the withdrawal of the ocean from the continent, accompanied by mountain-foldings from Mount St. Elias to the middle of the Aleutian peninsula, was probably due to the downsinking of the North Pacific Ocean basin.

Eurasia. In Europe the depression between the old land at the north and the Hercynian Mountains to the south continued. As during the Permian, the region was at this time a desert in which sediment washed from the mountains accumulated at their bases in alluvial fans and playas, whence the winds carried it far and wide; for these deposits of early and late Triassic age are characteristically cross bedded, some of the rocks being solidified dunes of red sands. In places where the streams were sufficiently large to survive the hungry sands of the desert, lakes developed, which, lacking outlets, formed gypsum and salt deposits.

The West Mediterranean basin, including eastern Spain, the lowlands of the Pyrenees geosyncline, and southern France, was, during the early and later Triassic, likewise a desert with deposits similar to those of the northern basin. The thickest deposits known occur near the center of the basin, on the Balearic Islands. To the west of this region there were probably mountains which shut off the moist winds from the Atlantic. During the middle Triassic these northern and southern desert areas were flooded by normal ocean waters.

From the region of the northern Alps, east through the Black and Caspian areas, and, more or less continuously, through the Himalayan region of southern Asia, extended the Tethys sea, with a normal marine fauna. Probably in marginal lagoons bordering this great Mediterranean accumulated such Triassic salt deposits as those now worked so extensively at Salzburg, Hallstatt, and Berchtesgaden.

JURASSIC

America. As during the Triassic, the continent of North America was largely subject to erosion. The only low areas with accumulating sediments were in the west. The western geosyncline, through California, Oregon, and Washington, was occupied by ocean waters with an abundance of life. The eastern geosyncline was largely marine at the southeast in western Cuba, Texas, and eastern Mexico, and in the northwest in Alaska; but in its medial portion, in what now forms the states of Arizona and New Mexico, and north to Alberta, desert deposits of white or red sands are the rule. In the later Jurassic the sea advanced southward over this desert area to northern Arizona. Thus in southern Utah there were first deposited upward of a thousand feet of pure white dune sands, now forming the White Cliffs, and later much thinner marine beds.

In South America the Andes geosyncline continued as a region of accumulation of sediments. The higher lands which bounded this region on the west are now mostly submerged beneath the waters of the Pacific.

Eurasia. In Europe the three broad Triassic depressions continued in general to be the areas of deposition, though they were at this time mostly marine. The northern basin, extending from Scotland south through England and east into Germany, was bounded on the west by the Armorican land mass, of which there now remains above the Atlantic only western France and Spain. The West Mediterranean basin was joined through the Alps depression with the East Mediterranean basin, whence the Tethys sea extended eastward through southern Asia.

During the middle Jurassic there was some emergence, but during the later part of the period, as in North America, there occurred a more extended submergence throughout Europe, and southward from the Arctic Ocean in northern Siberia.

Life of Jurassic time. The Jurassic seas, judging from the fossils of the period, swarmed with animals preying one upon another. Here were the more or less stationary sponges, corals, and pelecypods, while crawling over the bottom or swimming through the water were snails and crustaceans, cephalopods (such as ammonites (Fig. 124), and primitive squids,— belemnites (Fig. 124)), fish, and reptiles. Some reptiles, such as plesiosaurs and the dolphinlike, gregarious ichthyosaurs (Fig. 129), had by this time become as thoroughly adapted to an aquatic life as has the modern whale, for, bearing their young alive (see page 358), they need not crawl out upon land even to lay eggs. That some of these animals were very destructive is shown by the fact that within the stomach of one ichthyosaur were found the remains of more than two hundred belemnites. Upon land, roaming among the forests of cycads, conifers, ginkgos, and their undergrowth of ferns and rushes, were dinosaurs, turtles, and lizards; while flying in the more open spaces, partly in search of the numerous dragon flies, cockroaches, locusts, ants, and beetles, were flying reptiles and reptilian birds.

Mountain-building. At the close of the Jurassic the western geosyncline in North America was folded and uplifted; of these mountains the Sierra Nevada, the Humboldt Range of Nevada, and the Cascades are reëlevated remnants. Upon the old lands to the west of these mountains a new geosyncline was formed in which accumulated great thicknesses of sediment during the ensuing Lower and Upper Cretaceous periods, but whose bordering highlands upon the west are now beneath the ocean. Accompanying this elevation there occurred a great upwelling of lavas, which were poured out upon the surface or intruded as huge batholiths of granodiorites. These batholiths extend from Lower California to Alaska. The uprising molten rocks were accompanied in California by vapors bearing gold, which was deposited in quartz veins and became the source of the great gold deposits of that state.

LOWER CRETACEOUS

America. In North America the geosyncline which developed in the old land to the west of the folded Sierra Nevada and other mountains, at the close of the Jurassic, extended from California to Alaska. Westernmost California formed part of its western upland, and the newly elevated mountains its eastern margin. The sea had access to most of this depression. What is now the Queen Charlotte Islands was then swamp land, developing coal. In California there were deposited during the Lower Cretaceous (Knoxville and Horsetown formations) 26,000 feet of sandstone and shale; that is, when the last of this sediment was being deposited that laid down at the beginning of the period was at a depth of five miles,—the depth of abyssal seas today. This depression took place gradually, for from bottom to top the sediment has shallow-water characteristics and the fossils are marine, shallow-water forms, showing that as the geosyncline sank the bordering lands rose, thus continuing the supply of eroded material.

At the close of the Jurassic the formation of the Sierra Nevada and associated ranges had shifted slightly eastward the western margin of the interior (Coloradoan) geosyncline. The northern portion, from Colorado into British Columbia, was occupied by sluggish streams flowing from the mountains at the west, for the finer muds are to the east. The region was probably much like the great plains of China today. Between the interlacing streams were many broad swamps and lakes, in which flourished some of the largest land animals known (herbivorous dinosaurs), where food was plentiful and progression easy. These vast swamp lands extended from Colorado and Wyoming (Morrison formation, with its lower portion of late Jurassic age (Fig. 88)) into eastern British Columbia (Kootenay formation, with its abundance of coal). Farther south, from southern Colorado and Oklahoma through Texas, southern Arizona, central and eastern Mexico, and most of Central America to northern Colombia and Venezuela, the geosyncline was occupied by the waters of the Atlantic Ocean. These Lower Cretaceous deposits are known as the Comanchean series. Their waters were characterized especially by bizarre, thick-shelled pelecypods (Requienia, Monopleura, etc.). Since a very similar fauna existed in the seas covering southern Spain and the lands now bordering the Mediterranean, a short route for the intermigration must have existed. This connecting strand line was probably the northern shore of that portion of the Gondwana continent which is supposed to have connected South America with Africa; along this line the fauna would be in the same climatic belt.

Fig. 88. Mesozoic formations east of Newcastle, Wyoming

The massive bed in the middle of the slope is Jurassic sandstone (Sundance formation). The summit of the hill is composed of Lower Cretaceous shales (Morrison formation). The hard, white bed near the base of the section is gypsum at the top of the Spearfish formation (Triassic?). (Photograph by N. H. Darton. Courtesy of the United States Geological Survey)

A sediment-gathering zone was likewise present east of the Appalachian Mountains, extending from eastern Maryland and probably from eastern New England, south through Virginia to Georgia. The sediment (Potomac formation), accumulating in the form of alluvial fans and deltas, contains only land animals and plants. During the accumulation of the earlier beds, throughout the earlier part of the Lower Cretaceous, the animals (largely dinosaurs and other reptiles) and plants were closely related to those then living in the interior of North America (preserved in the Morrison formation), and more distantly to those flourishing at the same time in northwestern Europe and inclosed in the Wealden sediments.

Earliest flowering plants. It is in sediment deposited during the later part of the Lower Cretaceous that the first recorded appearance of flowering plants, the angiosperms, now the dominant plant life of the earth, is found. It consists principally of the poplar, which, with several more doubtful forms, occurs in the Kome beds of the west coast of central Greenland. By late Lower Cretaceous (Albian) time this flora, greatly enlarged, had spread through North America south at least to the Black Hills (Fuson formation) and in the Atlantic states to Maryland and Virginia (Patapsco formation). In Europe it had spread south to Spain. In the Patapsco formation, for example, both divisions of the flowering plants occur; there are three species of monocotyledons, including a representative of the sedges, and twenty-five species of the dicotyledons, including Populus, Sassafras, Celastrus, and Aralia. Immediately below the Patapsco there are no flowering plants, which indicates their migration into this region during the later part of the Lower Cretaceous time. Evidently this hardy flora had evolved somewhere in the lands surrounding the Arctic Ocean and, when physical conditions permitted, migrated southward. During the Upper Cretaceous it became the dominant flora of the globe.

Eurasia. In Europe the principal topographic features were the northern and the southern basins, separated by a land mass trending east-west through central Germany. The deeper portions of both of these basins were filled with the waters of the ocean. The northern basin, extending through northern Germany into central Russia, whence it was connected northward west of the Ural Mountains with the Arctic Ocean, naturally had a northern fauna, including such forms as Aucella and characteristic ammonites very similar to those of the west coast of North America. The southern, or Mediterranean, basin (Tethys) included the western Mediterranean basin, with its connection through southern Spain with the North Atlantic basin, and the area eastward through the Alps and the Black and Caspian seas, and thence through southern Asia. Tethys covered a small portion of northernmost Africa, but Asia Minor and Arabia still formed part of the African continent. Upon the northern and western margins of these European basins continental deposits, largely of delta origin, were formed; these had been eroded from the higher lands to the north and west. In southeastern England these deposits (Wealden) reach a thickness of several thousand feet; they attain a similar thickness in northeastern Spain.

Associated probably with a depression of the basin of the Pacific Ocean, an uplift occurred in western North America, raising what is now the region of the intermontane plateaus, extending from Alaska to Central America. At the same time it caused a broadening of the geosyncline bounding its eastern margin, including the region now occupied by the Rocky Mountains and the interior plains to the east. Through this depression the waters of the Gulf and Arctic were united during the following Upper Cretaceous time.

UPPER CRETACEOUS

During the Upper Cretaceous all the widely peneplained lands of the earth were subject to a phenomenal submergence. By the middle portion of this period central North America from the Arctic to the Gulf was submerged, as were also the region of the present Andes Mountains in South America and the Amazon valley. Central and southern Europe were reduced to an archipelago; Egypt and the Sahara were flooded, as were southwestern Asia, many of the East Indies (as Borneo), and northern Australia. To bring about such a submergence of lands in all parts of the world there must have been a rise of ocean level. This may have been due to the foundering of large land masses, such as portions of Gondwana.

North America. *Physical features.* Throughout the Upper Cretaceous decided uplands in North America were few and small in extent. In the east the Appalachians were largely worn down to a low, level plain, over which lazily meandered the Delaware, Susquehanna, Potomac, James, and other rivers (Figs. 89, 90, 91). By this time the Appalachian Mountains (folded during the Permian) had been reduced by rain and the resultant streams to a low plain, truncating hard sandstone and soft shales to a common level. In Fig. 89 the truncation of a simple anticline is shown; the inset represents two of the dinosaurs living at this time, the carnivorous Tyrannosaurus and the herbivorous horned dinosaur Triceratops. Fig. 90 (a view of the same region) and Fig. 91 (a photograph of a characteristic portion of the Appalachians) are inserted here to show the character of the changes that have taken place from the close of the Cretaceous to the present. The level tops of the higher mountains (upwards of 2000 feet above sea level) are the only remnants of the Cretaceous plain. At the close of the Cretaceous and at the beginning of the Tertiary the region was elevated. During the Tertiary it was reduced to a plain (the 700-foot level) except for the harder rocks (remaining at the 1500-foot level). During the Pliocene it was again elevated several hundred feet; since that time it is gradually being reduced to a new and lower peneplain (the bottom of the valleys). The inset of Fig. 90 shows the present life of the region. These figures thus indicate three periods of upheaval and of erosion: (1) folding and upheaval at the close of the Paleozoic and erosion throughout the Mesozoic, producing the Cretaceous peneplain; (2) upheaval without folding from the close of the Cretaceous into the Paleocene and erosion during nearly all Tertiary time, forming the Tertiary partial peneplain; (3) upheaval during the Pliocene and erosion to the present, giving rise to the present valleys and flood plains.

The present Rocky Mountains were beneath the ocean waters (Figs. 92, 93) or were at a critical level, receiving alternately marine and continental deposits. Fig. 92 represents a section beneath the ocean floor and shows the sediments deposited here during the Upper Cretaceous. The sandstone at the base is

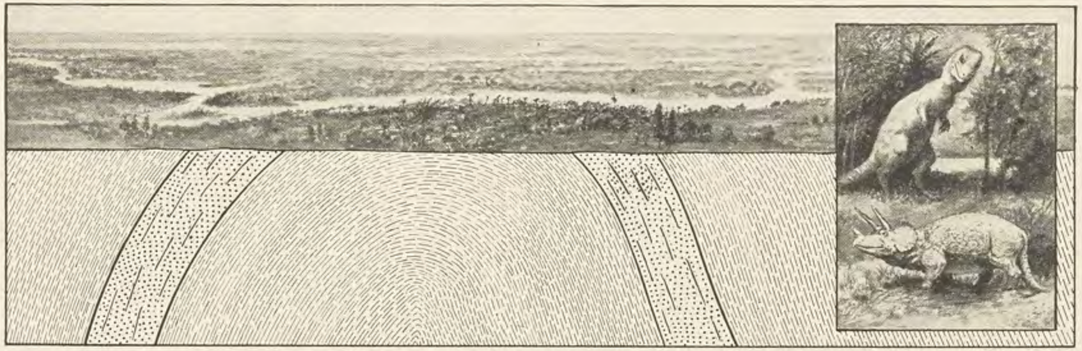


Fig. 89. The Appalachian region during the Upper Cretaceous (generalized for eastern Pennsylvania)

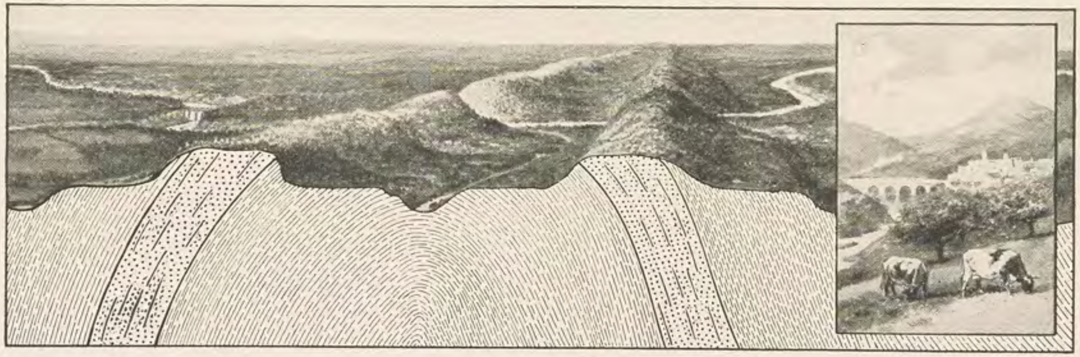


Fig. 90. Bird's-eye view of the same portion of the Appalachian region (shown in Fig. 89) as it is today

the Dakota sandstone. The inset represents some of the life of these seas: a plesiosaur at the left, pursuing the bird Hesperornis, which in turn is diving after a fish. Above is the flying reptile Pteranodon. Fig. 93 represents the same region as it is today. The sediments which had been deposited in the sea during the Upper Cretaceous and older periods were folded and uplifted into the Rocky Mountains at the close of the Mesozoic and again during the later Tertiary; since then they have been subject to erosion. The conspicuously resistant layer to the left of the middle of the section is the Dakota sandstone, the source of most of the artesian water of the plains today.

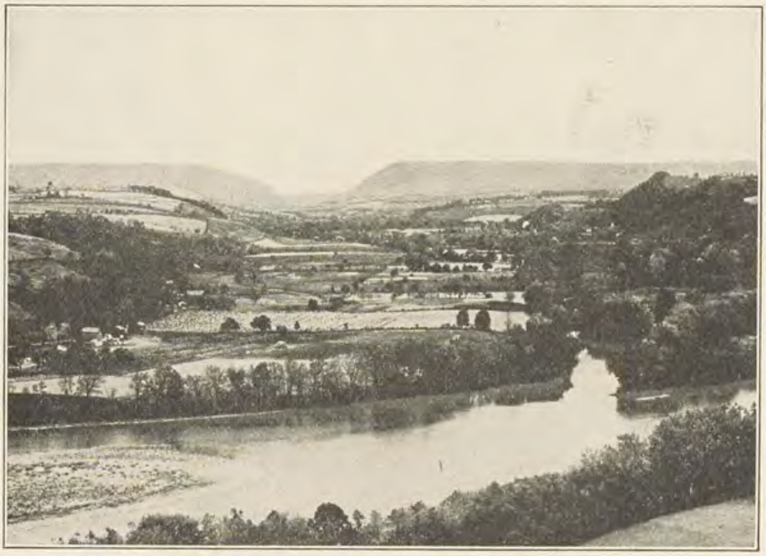


Fig. 91. Delaware Water Gap, looking north

The surface of the Kittatinny Range in the background is a remnant of the peneplain developed in the Appalachian region during the Mesozoic era. This Cretaceous peneplain was raised about 1500 feet at the close of the Mesozoic. During the Tertiary the softer rocks were eroded, leaving the harder rocks, such as those forming the Kittatinny Range, projecting above the general level. This lower level is the Tertiary partial peneplain, seen in the foreground as a terrace upon each side of the present valley. At the close of the Pliocene the whole Appalachian region was raised about 500 feet; since that time the Delaware River has carved its present valley toward the production of a new peneplain at this level

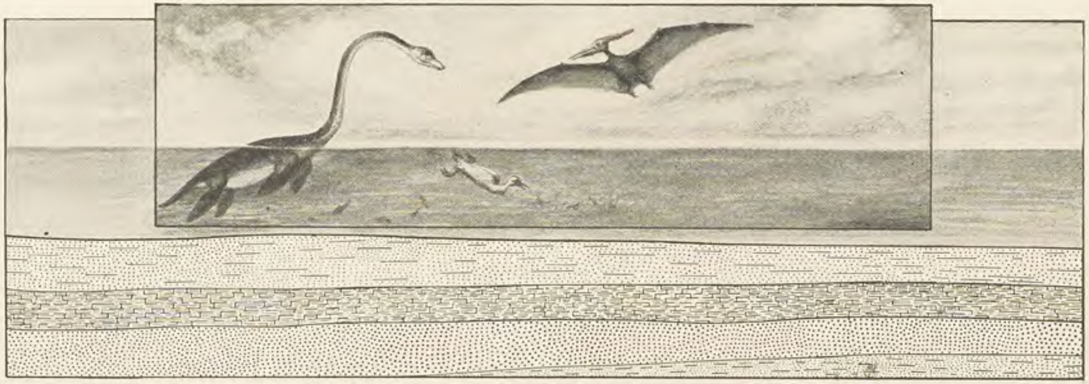


Fig. 92. The interior sea of North America during the Cretaceous (this is the region shown in Fig. 93)

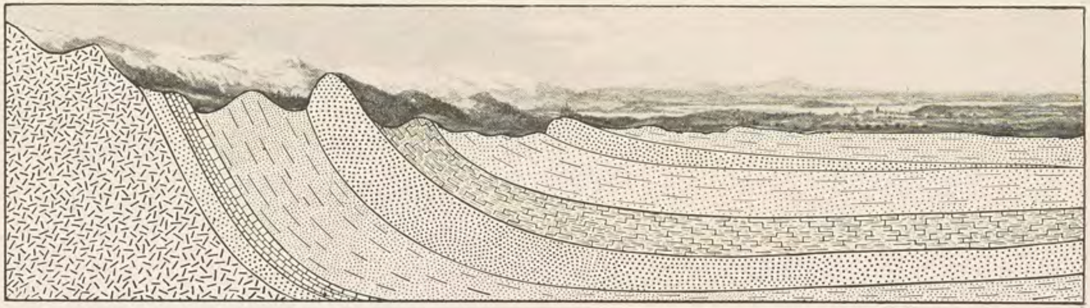
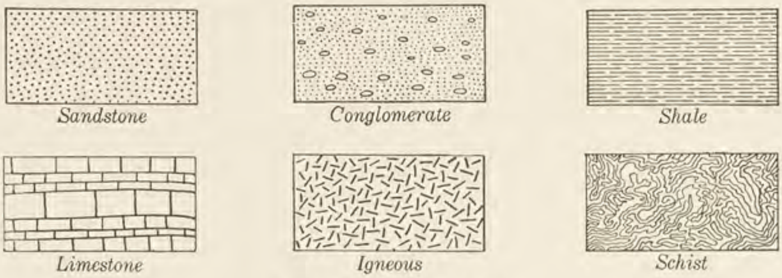


Fig. 93. Generalized bird's-eye view from the Rocky Mountains in Colorado eastward, as it is today

The western continent of North America, between the inland sea and the Pacific, was likewise comparatively low, as is shown by the fine sands and muds deposited upon both its eastern and western margins. But the lands bordering the western shores of the great interior sea were higher than the regions to the east, as is indicated by the amount and kinds of sediment which the rivers from both sides carried into this sea. Of all such deposits the sands and muds are thickest in eastern Wyoming and Colorado, becoming thinner and much more calcareous eastward into the Dakotas, Nebraska, and Iowa.



Sandstone *Conglomerate* *Shale*

Limestone *Igneous* *Schist*

Fig. 94. Rock symbols

Combinations of these symbols indicate combinations of rock material, as sandy shales and shaly limestone

In eastern North America the Atlantic Ocean submerged the present marginal lands from New England south,— evidence that the sinking of the North Atlantic Ocean basin at the beginning of the Upper Cretaceous had drawn beneath its waters that portion of the old land mass that lay to the east of the present eastern margin of North America (Fig. 95). The Atlantic also extended as a narrow embayment along the present west coast of Greenland. In west-central Greenland marine beds on the west and continental beds east of them indicate that the relation of land and sea was as it is now. That the Newfoundland-Nova Scotia land mass projected farther eastward than it does today is indicated by the absence of marine Cretaceous sediments. A little later in the Upper Cretaceous an extension of the Atlantic submergence carried the ocean waters over the eastern Gulf states.

The Pacific coast was similarly submerged along its margin or had an embayment into what is now the marginal lands of California, Oregon, Vancouver Island, and north.

The great interior sea. The marine waters at their maximum extent bisected North America longitudinally, uniting the Arctic Ocean and the Gulf of Mexico. Since the waters overran lands which for ages had been subject to weathering, they carried the comparatively small amount of finer muds seaward, depositing the more resistant quartz sands as a basal bed (Dakota sandstone etc.) (Fig. 96). As the shores receded during the progressive submergence, sands, sandy muds, and at times chalk (Niobrara, Selma) were deposited. Some of the muds, such as the Benton, abound in fish remains, the probable source of much of the petroleum since stored in the more porous beds. In the swamps bordering this inland sea upon the low-lying, slightly warping, western border, an abundant growth of ferns, aided by higher plants, gave rise to deposits of carbonaceous matter now altered into the bituminous coal of the Rocky Mountain region. Such coal-producing swamps were especially numerous during the time that the ocean waters were being withdrawn during the later part of the Upper Cretaceous.

Fig. 95. East-west section southeast of Trenton, New Jersey

This is a characteristic section of the coastal region of eastern North America illustrating the submergence of the old land of Appalachia during the Upper Cretaceous. (After F. Bascom)

Animal life of the interior sea and its shores. The interior seas of North America, extending from northern South America to the Arctic Ocean and from Utah and western Alberta eastward to western Tennessee and Manitoba, swarmed with life (Fig. 97). Floating in the water or resting upon the ocean floor lived many microscopic one-celled animals and plants, similar to those forming the Cretaceous chalk of Europe. Similarly in North America these calcareous skeletons at times formed chalk (Niobrara, Selma) in places where the water was free of sands and muds. Upon the ocean floor lived many kinds of oysters and other shelled animals, while crawling or partly swimming over these in search of food were crustaceans and especially large numbers of ammonites (Fig. 124) clothed in multiform shells. Fish were likewise very abundant, from ancestral salmon and iridescent ganoids to rapacious sharks. One of the most terrible of the fish was the bulldog fish (*Portheus molossus*). He was seven feet long and had a skull the size of that of a grizzly bear, with numerous teeth rising three inches above the gums of his deep jaws. Diving birds such as Hesperornis (Fig. 97), three feet high, preyed upon the smaller fish. Ichthyornis was smaller and ternlike. The air was dominated by the leathery-winged reptiles, the pterodactyls. One of these, the huge Pteranodon, had a skull thirty inches long and a probable spread of wings of twenty feet (Fig. 97). At home upon the open seas were representatives of two orders of reptiles, plesiosaurs and mosasaurs. The plesiosaurs, seal-like in their two pairs of paddles but comparatively slow and stupid, varied

Fig. 96. Typical cliffs and talus of the massive Dakota sandstone (Upper Cretaceous), east of Newcastle, Wyoming

Photograph by N. H. Darton. Courtesy of the United States Geological Survey

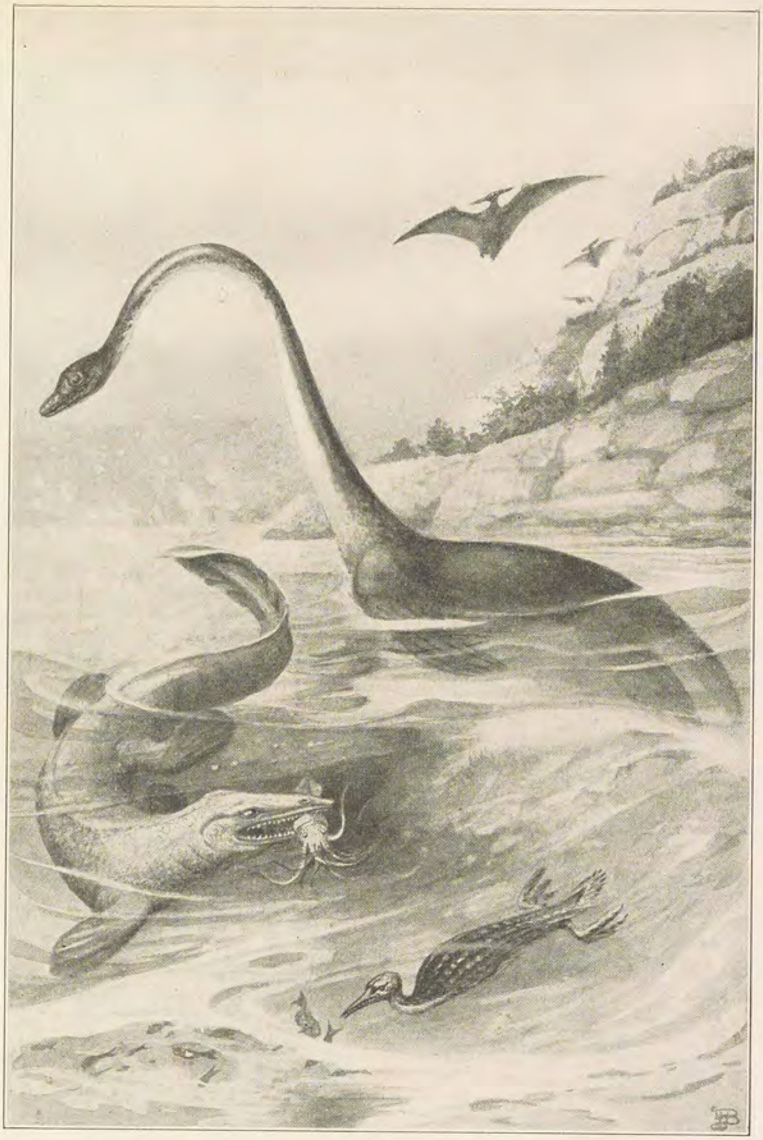


Fig. 97. Life of the great interior sea that separated North America into an eastern and a western continent during the Upper Cretaceous

The mosasaur Clidastes is represented catching a squid (Belemnites); the wingless, toothed bird Hesperornis is diving for fish; swimming at the surface is the plesiosaur Elasmosaurus; in the air are flying reptiles (Pteranodon) in length from ten to fifty feet, half of which length belonged to the slender neck. The teeth of some of the larger forms had a length of four inches. But the rulers of the seas, as of the oceans of the world, were the mosasaurs, veritable sea serpents. Some of these reptiles reached a length of forty feet; this, with their slender jaws three feet long, filled with recurved teeth projecting two inches above the gums, gives indication of their powers and voracity (Fig. 97).

Crocodiles and turtles searched for food in the marginal waters and on the neighboring land. One of the larger turtles, Protostega, had a length of twelve feet. Upon the lower-lying lands lived many dinosaurs, both vegetable feeders and carnivores. Of these the duck-billed dinosaur Trachodon has been found over a range extending from New Jersey to Mississippi, and from Dakota to Montana. It was over sixteen feet high from the head to the ground, and had a flattened, ducklike bill covered with horn, with which it fed upon soft herbage. With it fed small herds of Triceratops (Fig. 89). This reptile was larger than a rhinoceros, with head armed with a huge, turtlelike beak and three forward-projecting horns; its skull extended backward over its neck in a huge projecting frill. The tyrant saurians (Tyrannosaurus), standing twenty feet from head to ground and armed with huge teeth and sharp claws, must have been the ferocious enemies of all other animals of that time (Fig. 89).

Mammals were a decidedly subordinate element in the life of the Upper Cretaceous. Few of them were larger than rats. Some, as shown by the shape of their teeth, were carnivorous; others ate also fruit. It was probably by living among the rocks or in the branches of trees that these small animals survived the numerous huge reptiles of the time.

Plant life of North America. The hardy and energetic flowering plants spread over the entire continent of North America during the latest Lower Cretaceous time and the very early Upper Cretaceous, evolving new species as time passed and they entered new environments. They comprised, during the Upper Cretaceous, a vast number of species and had become the dominant feature of the vegetation. Their fossil remains, known from Greenland to Alabama and from Massachusetts to California, give evidence that they covered all land areas. The presence of many similar species throughout this area, and of the fig, cinnamon, and magnolia in Greenland as well as scattered over the remainder of the continent, indicates a rather uniform warm-temperate or subtropical climate. The flora comprised, among monocotyledons, the sedge, cat-tail (Typha), and Smilax. Among the dicotyledons may be noted the willow (Salix), poplar (Populus), walnut (Juglans), oak (Quercus), birch (Betula), elm (Ulmus), maple (Acer), hickory (Carya), tulip tree (Liriodendron), Sassafras, fig (Ficus), plane tree (Platanus), Eucalyptus, shadbush (Amelanchier), sumach (Rhus), laurel (Laurus, Kalmia), cinnamon (Cinnamomum), holly (Ilex), bittersweet (Celastrus), cornel (Cornus), waxberry (Myrica), wild sarsaparilla (Aralia), Viburnum, Cassia, Ceanothus.

Next in importance to the dominant flowering plants were the conifers, which included Ginkgo, Sequoia, pine, juniper, Araucaria, Abietites. Among the ferns were such modern genera as Dryopteris, Asplenium, Dicksonia, Marattia, Woodwardia, and Onoclea. The cycads were declining rapidly. The club mosses are known in the modern genera of Lycopodium and Selaginella. Horsetails are rare, represented by Equisetum. Liverworts, algæ, and fungi are likewise rarely preserved.

Thus it is evident that in North America, millions of years ago, the plant life had a very modern appearance, many of the modern genera of trees being present. There were, however, none of our modern species, and there was a much smaller proportion of herbs and of monocotyledons than at present. There were here associated genera which the diversified climate of later geological times and other vicissitudes have widely separated.

Central and South America. Southward the Gulf of Mexico submerged Cuba and Jamaica. In this area Upper Cretaceous beds rest upon old crystallines, probably of pre-Cambrian age, indicating a breaking up of this old West Indian land mass. Farther southward the Gulf expanded into Colombia and Venezuela, and extended eastward through the Caribbean area into the Atlantic, where, along the partly submerged Gondwana land mass, such shallow-water forms as the bizarre pelecypods Rudistes and Caprina intermigrated between the Gulf of Mexico and the Tethys sea of Europe.

The waters of the Gulf, with their characteristic fauna, also extended south through the Andean geosyncline of Peru, Bolivia, Chile, and western Argentina. In other words, the region of the present Andes Mountains was an elongated depression filled by ocean waters, like the Gulf of California or the Japan Sea today. That this trough was bounded on the west by a land mass, now submerged beneath the waters of the Pacific, is shown by the fauna, which was very different from the contemporary fauna of California.

Eurasia. In Europe, following the shoaling of the waters at the close of the Lower Cretaceous, there took place during the Upper Cretaceous another period of great submergence. Again the northern and southern basins were in evidence, though much expanded and filled with ocean waters. The northern basin, extending over England and northern France and through northern Germany, was a clear sea in which there developed the deposits of chalk so well exposed today in white cliffs on the Isle of Wight, at Dover in England, and at Calais in France. The broad northern lands were apparently so low as to give to the streams little but the soluble products of rock decomposition. In these shallow waters, and even near shore, the skeletons of the innumerable one-celled animals and plants which lived floating in the water or resting upon the ocean floor could very slowly accumulate to a great thickness. Since the vast majority of such skeletons were calcareous, the resultant accumulation was chalk. Especially numerous were the protozoöns, — Globigerina and Textularia. Among these calcareous skeletons were scattered some siliceous protozoön skeletons (Radiolaria) and sponge spicules. The silica, being in the colloidal state, was easily dissolved by percolating alkaline waters; collecting in masses, it was redeposited along bedding planes in a more stable form, thus forming the flint nodules abundant in some of the chalk.

The southern basin, the Tethys sea, partially separated from the northern basin by a narrow east-west-trending land mass

(Vindelicia), abounded in such shells as Rudistes and Caprina, which, as they accumulated, formed great limestone deposits. Where these seas extended over lands long subject to weathering, sandstone deposits were formed, as in Bohemia and in Saxony (Quader sandstone) and in northern Egypt (Nubian sandstone).

Continental elevation at the close of the Cretaceous and the consequent destruction of decadent species. At the close of the Cretaceous and continuing into the early (or Paleocene) Tertiary occurred a period of widespread mountain-folding and plateau-like uplift, accompanied by a pronounced depression of ocean basins. This brought about such a widespread and lasting change in the relation of continent to ocean, and consequently in ocean currents and climate, and was necessarily accompanied by so radical a change in the higher animal life, that it has naturally been made the basis of a major division in earth chronology. It records the change from the medieval era of earth history to the modern era, from the Mesozoic to the Cenozoic.

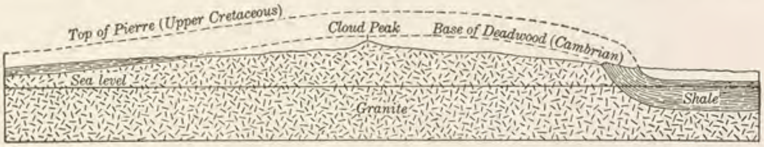


Fig. 98. Late Cretaceous and Tertiary folding

East-west section across the highest part of the great anticline forming the Bighorn Mountains, showing amount of erosion. This great anticline, raised at different times during the Tertiary (especially Paleocene and Miocene-Pliocene) to a total height of about 25,000 feet, extends from southern Montana 125 miles southeast to central Wyoming. It brought up the Paleozoic and Mesozoic formations with a central nucleus of pre-Cambrian granites, from which the sediments dip away on either side, showing the extent of erosion of uplift. The faulting is not shown. (Vertical and horizontal scales: 1 inch = 10 miles.) (Cross section by N. H. Darton. Courtesy of the United States Geological Survey)

During this period of terrestrial unrest the Rocky Mountains from Alaska to southern Mexico were folded and faulted (Fig. 93). At the same time the region between the Rockies and the Pacific suffered many changes of level and in some places mountain-making and intense metamorphism; the Appalachian Mountains likewise experienced a differential uplift of some 1500 feet (Fig. 90). In South America the Andes Mountains from Colombia to Cape Horn were folded and uplifted. If, as is usually postulated, the rise of these American mountains was caused by a downsinking of the Pacific Ocean basin, such explanation would likewise account for the withdrawal of the ocean waters from all other continents at this time.

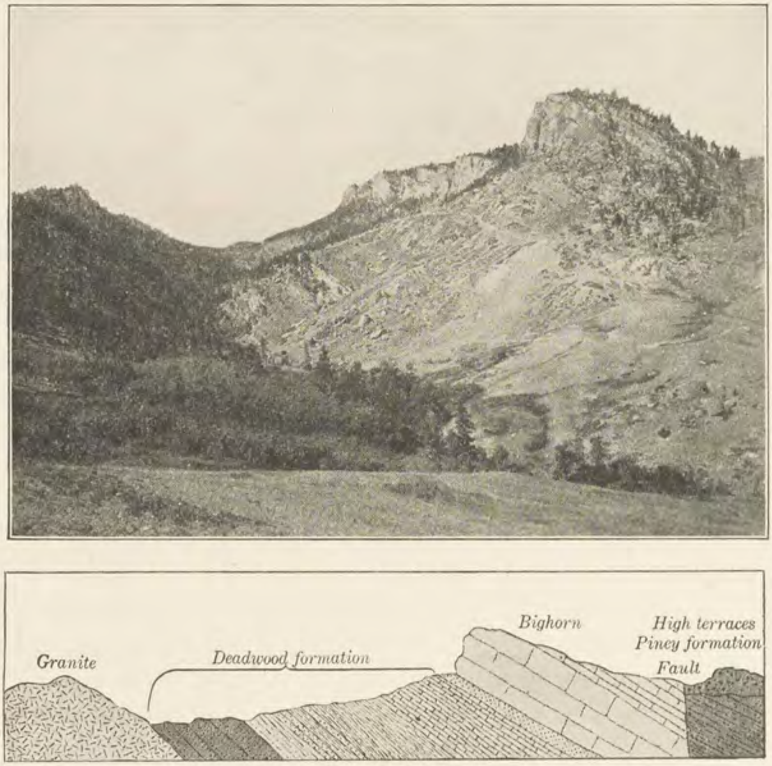


Fig. 99. Late Cretaceous and Tertiary folding

View (northwest of Buffalo, Wyoming) of the eastern limb of the great anticline forming the Bighorn Mountains. The relation of the beds is seen in the key section at the base. The granite is of pre-Cambrian age, the Deadwood formation is Cambrian, the Bighorn formation is Ordovician, and the Piney formation (east of the fault) is Upper Cretaceous. (Photograph by N. H. Darton. Courtesy of the United States Geological Survey)

The upheaval of mountains and the great increase in the size of the continents during the late Cretaceous and Paleocene

Tertiary initiated climatic and other physical changes. Highly specialized plants and animals gradually disappeared,— those too confirmed in old habits to be able to meet the new physical environment. The great amount of energy with which each new species begins its earthly life was apparently, in the case of many of the organisms, thoroughly exhausted by the close of the Mesozoic. Hence with lessened vitality they could not meet the changed conditions. Thus perished at this time the great reptilian orders for which the Mesozoic was especially noteworthy,— the huge land dinosaurs, the swimming reptiles, and the flying reptiles, all with a low type of brain and organization. The ammonites and belemnites among cephalopods disappeared completely, while the toothed birds were replaced by the more agile modern toothless birds.

TOPICAL REVIEW

- Triassic
  - America
    - Marine deposits
    - Continental deposits and the life of the lands
  - Eurasia
- Jurassic
  - America
  - Eurasia
  - Life of Jurassic time
  - Mountain-building
- Lower Cretaceous
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    - Physical features
    - The great interior sea
    - Animal life of the interior sea and its shores
    - Plant life of North America
  - Central and South America
  - Eurasia
  - Continental elevation at the close of the Cretaceous and the consequent destruction of decadent species

CHAPTER XV

CENOZOIC

There rolls the deep where grew the tree.
  O earth, what changes hast thou seen!
  There where the long street roars hath been
The stillness of the central sea.
TENNYSON

The Cenozoic, the latest era of earth history, began with the continents comparatively high and broad. Gradually the seas encroached upon their margins. Then followed a withdrawal of ocean waters during the world-wide mountain-making period of the later Tertiary. The Cenozoic began with local mountain glaciers, passed through a warm period, and then experienced one of the greatest glacial periods the earth has known. During this (Pleistocene) glacial period northern North America and northwestern Europe were covered with continental ice sheets, while local mountain glaciers were very numerous throughout the world. Eight million square miles were covered with ice sheets. We are living today in what may be the closing stage of this glacial period.

During the Cenozoic, erosion products accumulated in local basins throughout North America, especially between the ranges of the Rocky Mountains and upon their eastern flanks, as well as upon the plateau and Pacific coast regions to the west. In lakes and bogs, upon alluvial fans and flood plains, or as wind or volcanic deposits, wherever they were protected from erosion, these products gathered, covering whatever remains of plant or animal life were present. It is from these deposits, laid down at various times during this era, that a knowledge of the remarkable mammalian life of North America is largely derived.

The Cenozoic era merits its name of "recent life," for throughout this period modern types of plants and animals are everywhere dominant,— mollusks on the floors of water bodies, squids and bony fish in the waters, mammals on land and in fresh water and the marginal and open seas, toothless birds in the air, and flowering plants both on land and in fresh waters.

The closing days of the Mesozoic saw the disappearance of about 40 per cent of the Cretaceous genera of plants (Knowlton). Of all the hosts of marine ammonites and squidlike belemnites none remained at the opening of the Cenozoic. Of the vast number of reptiles which gave character to the Mesozoic, only crocodiles, turtles, lizards, and snakes survived. All the flying, swimming, and dinosaurian land reptiles had disappeared. Thus, while so much of the life most characteristic of the Mesozoic had vanished at its close with a completeness and suddenness but partially explained by the changed physical conditions, the most characteristic forms of Cenozoic life, the large-brained mammals, did not appear in any number until the Eocene. During the interim, the Paleocene, the descendants of the known Mesozoic mammals of Europe and America expanded to fill some of the vacant habitats. These, however, continued to be, like their archaic Mesozoic ancestors, very primitive and small (none larger than a sheep), with small brains and with five digits on fore and hind feet, and nearly all with the habit of walking upon the flat of the foot. Some of the descendants of these very primitive orders are with us today, — the opossum of the marsupial order, the sloth of the edentates, and the mole of the insectivores, all surviving only because they do not enter into direct competition with the higher orders.

Beginning in the Paleocene but especially active during the Eocene, a migration from the north of large-brained mammals invaded simultaneously both North America and Europe. Before leaving their home land (possibly Asia) they had already differentiated into such modern orders as rodents, odd-toed and even-toed ungulates, and primates. Thus there arrived in North America during the Eocene the primitive horse, tapir, camel, rhinoceros, lemur, and monkey. Similar migrations between the different continents continued at intervals throughout the rest of the Cenozoic.

The glacial period, referred to briefly in the following discussion of the Cenozoic, is discussed in detail in Chapter XVI.

NORTH AMERICA

Throughout its long history North America has been continuously characterized by eastern and western highlands and an interior lowland. During the Upper Cretaceous the interior lowlands, as well as what are now the Rocky Mountains, were largely covered by ocean waters. Possibly also during the Cretaceous the old southern highlands were depressed, forming the Gulf of Mexico. Northeastern Canada and Greenland have always been the most persistently, though slowly, rising portion of the continent. The eastern and western portions were always the most unstable, parts sinking to great depths as geosynclines and then rising into mountains, while at the same time these margins have gradually moved inward, submerged beneath the encroaching oceans. Apparently somewhat later the southern margin also became unstable. The medial portion has always remained the most stable, either just above or just below sea level. Hence broad areas of the oldest rocks are exposed at the surface in the northeastern part of the continent, the most complete series of rocks of all ages in the strongly folded eastern and western regions, while the interior plains from the Arctic Ocean almost to the Gulf of Mexico are characterized by horizontal sediments; these still remain, for the most part, in the position in which they were deposited.

Eastern North America

In eastern North America the plateau-like elevation of the Appalachian mountain region at the close of the Cretaceous brought a rejuvenation of the rivers upon this broad plain, the Cretaceous peneplain. Since that time the rivers have continued deepening and widening their valleys, until today the level of the old plain is seen only in the horizontal crests of the mountains. These mountains of the Appalachian, Blue Ridge, White, Green, etc. are merely the harder rocks not yet worn away, the broad lowlands being carved out of the softer rocks. Where the rivers cut through the harder rock ridges they have been able to develop only narrow valleys, as at the Delaware

Water Gap. By the Pliocene a partial peneplanation, limited to the softer rocks, had been developed, when an uplift of several hundred feet took place; since this time the streams have had time to sink only narrow valleys within the broad Tertiary ones (Fig. 91).

Between the withdrawal of the Atlantic Ocean eastward at the close of the Cretaceous and its return in the lowest Tertiary (recorded in the Shark River formation of New Jersey, of lower Paleocene age) the time was sufficiently long for the very slow processes of evolution and the more rapid ones of migration to produce a substantially new assemblage of organisms. Gradually, though accompanied by withdrawals, the waters of the Atlantic advanced westward until they had reduced the Atlantic states to half their present breadth; after which, with similar vicissitudes, they retired to their present position.

The Gulf of St. Lawrence is due to downfaulting during the latest Pleistocene, for no older marine fossils are known from its shores. The Newfoundland fishing banks are apparently the submerged delta of the St. Lawrence River. The river itself flows along a Paleozoic overthrust fault line (Logan's Line). To the north of the river the Paleozoic strata are horizontal; to the south they are contorted. This ancient fault line continues through Lake Champlain.

GULF OF MEXICO

It is doubtful if the Gulf of Mexico depression existed before the Cretaceous; since then it has grown southward and eastward through the foundering of the West Indian land mass. At different times, however, throughout the Mesozoic the waters of the Atlantic Ocean, probably by way of the Caribbean, flowed over parts of Mexico and Texas.

In the early Tertiary, to the north of the mountains upheaved in the West Indian region, the waters of the Gulf geosyncline spread west and north over Yucatan, eastern Mexico, and the Gulf states. Entering the downfaulted Mississippi embayment, they extended during the Eocene to southern Illinois. By the early Oligocene, elevation and the delta deposits of the Mississippi and its present branches had limited their northern extension to mid-Alabama. Gradually, with advances and retreats, the waters of the Gulf retreated to their present position, while the sediment deposited by the Mississippi has even caused an extension of the land at its mouth.

INTERIOR PLAINS

After the withdrawal of the seas in late Cretaceous times this region was subject to filling (mainly at the eastern base of the Rocky Mountains and upon the deltas of the Mississippi and Mackenzie rivers) and to erosion. By the Pliocene these two processes had given to the province the appearance of a plain, above which rose a few uneroded remnants, such as Turtle Mountain in North Dakota and southern Manitoba. During the Pliocene it was elevated several hundred feet, and since that time the streams have carved their valleys to maturity. Since the Rocky Mountains were elevated thousands instead of hundreds of feet during the Pliocene, the deposition of more material upon their eastern flanks than the streams could carry to the Gulf has resulted in the upbuilding of the High Plains extending from western Dakota, through western Nebraska, to western Texas. The dumping by the Pleistocene glaciers of great quantities of sediment throughout Canada and the northern states has partially or completely filled the late Pliocene valleys. This sedimentation has thus made these regions much more level than they would otherwise have been, and at the same time has brought into existence the numerous lakes and swamps so characteristic of them at present.

WESTERN NORTH AMERICA

Beginning in the late Cretaceous and continuing into the lower Tertiary, the Rocky Mountains were folded, in places reducing the width of earth surface sometimes to the extent of fifty miles, and producing mountains probably from 15,000 to 20,000 feet in height (Figs. 98–100). The region west to the Pacific was also elevated and much of it deformed. Throughout the lower Tertiary to the mid-Miocene, western North America was, in general, quiet, as was the rest of the continent, though in places, as in western Wyoming and Utah, there was some movement and some igneous activity. Throughout these ages of comparative stability nearly all of the continent, including the Appalachians, interior plains, Rocky Mountains, and west, was worn down nearly to a plain, with the majority of streams reduced to a low gradient. This comparative quiet was interrupted in mid-Miocene times by the beginning of deformative earth movements, caused probably by the deepening of the Pacific Ocean basin, which reached their climax during the

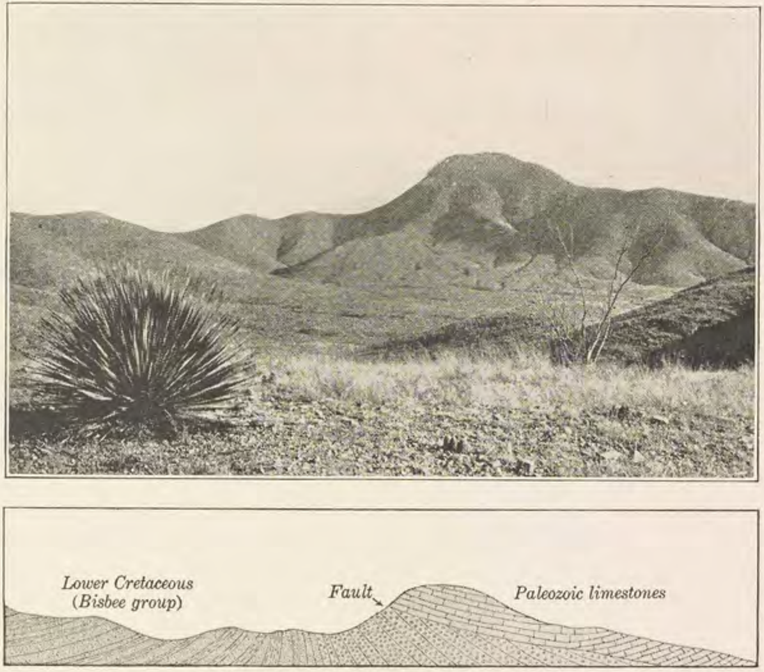


Fig. 100. Gold Hill fault near Bisbee, Arizona

Here, sometime after the Cretaceous, an overthrust of about two miles brought the Paleozoic limestones from the southwest up over the Lower Cretaceous. Note key section at base. (Photograph by F. L. Ransome. Courtesy of the United States Geological Survey)

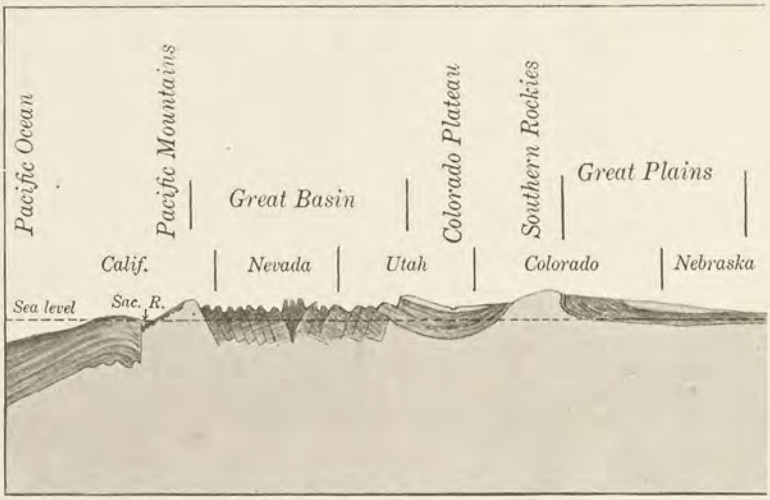
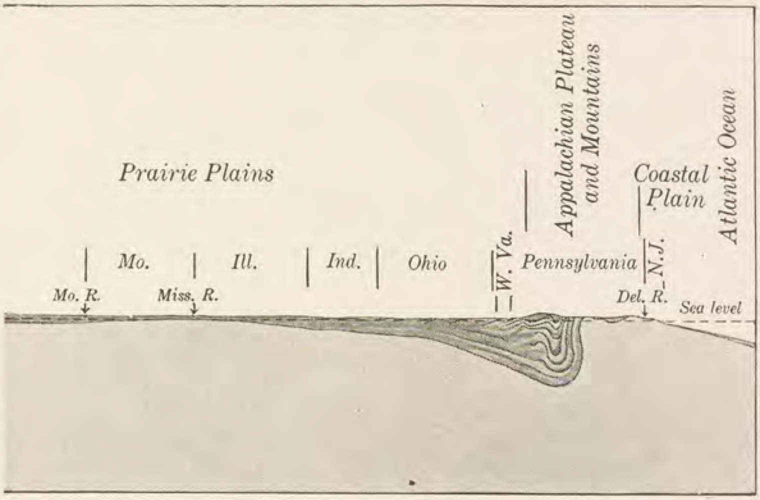


Fig. 101. Generalized section across the North America of today at parallel 40°. The Paleozoic, Mesozoic, and Cenozoic sediments (with a vertical exaggeration of 30 over the horizontal scale) are shown resting upon

Pliocene but continue to the present. The movements began principally in the western part of the continent with such upheavals as that of the Coast Range of California, such faults as the San Andreas, which extends 400 miles down into the Mohave Desert (a recent movement along the northern end of this fault gave rise to the San Francisco earthquake of 1906), and such volcanic activity as the great lava outpouring in Idaho, eastern Oregon, and Washington. The peneplain of western North America from the Rocky Mountains west developed during early and middle Tertiary times and was elevated during the Pliocene to a height of several thousand feet; since that time streams have cut away the softer rocks, leaving the harder ones projecting as mountains. But the work of water in the production of a rugged topography has been greatly aided by faulting, differential uplift, volcanoes, and Pleistocene and later glaciers.

Great Basin. Caterpillar Ranges. The block faulting of the Great Basin region, although initiated in the early Eocene, was to a large extent accomplished during the mid-Miocene to



the undifferentiated pre-Cambrian and deeper rocks of the earth. They descend into such deep synclines as the Appalachian, disappear entirely in the southern Rocky Mountains, and are greatly faulted farther west

Pliocene period, though it has continued, especially in the northern portion (southeastern Oregon) up to the present. The settling and tilting of the earth blocks between the north-south-trending faults have resulted in numerous block mountains, looking, from an aëroplane, with the sun low, like a procession of caterpillars. These block mountains extend from Nevada through Arizona into Mexico. The blocks in Nevada, sinking deeper than those in the surrounding regions, gave rise to the Great Basin; the western margin of this basin is formed by the eastern fault scarp of the Sierra Nevadas, and its eastern margin by the western scarp of the Wasatch Mountains at Salt Lake City (Fig. 101). Similarly, and at the same time, the Gulf of California was formed and also Death Valley in southeastern California. Salton Sink in southeastern California is the lowest point in the northern continuation of the Gulf of California, from which it has become separated by the building of the Colorado River delta. Portions of this sink are now irrigated and under cultivation,— Coachella Valley in the northern portion and Imperial Valley in the southern portion.

Volcanoes. Very frequently lavas arose through the cracks between these blocks, often accompanied by explosions and resulting in the upbuilding of low cones. Such upper Tertiary, Pleistocene, and recent lavas (Fig. 102) are not confined to the neighborhood of block faulting but are a common phenomenon in the United States west of the Rocky Mountains and south through Mexico, Central America, and western South America.

Fig. 102. View of West Spanish Peak from the northwest

From the region of this peak (the center of eruption) dikes radiate in all directions. In the foreground are shown one large dike and smaller ones. Horizontal Eocene strata outcrop on the middle slopes of the mountain. Successive eruptions and intrusions of igneous rocks took place here from late Eocene almost to the present. (Photograph by Stose. Courtesy of the United States Geological Survey)

Through the agency of these volcanoes there resulted, during the Miocene, the most spectacular preservation of forests known. In the Yellowstone National Park a section is exposed showing fifteen successive forests which were buried in the position of growth by ash from neighboring volcanoes. Since these trees occur through a thickness of 2000 feet of ash and lava flows, their preservation is probably associated with a gradual sinking of the region. After the overwhelming of a forest with a volcanic deluge a long time must necessarily have elapsed for the decay of the surface layers to form a soil from which the succeeding forest could derive nourishment (Fig. 103). Since the height of the trees preserved is usually less than twenty feet, it is evident that only the basal portion of the forests was surrounded with ash, the silica from which has effected their preservation. The trees, comprising such forms as the sequoia, walnut, magnolia, and fig, vary in diameter up to ten feet (Knowlton).

Fig. 103. A fossil tree trunk of the Miocene

This five-foot, high fossil trunk is seen in its place of growth beside a tree growing today. The tree was buried during the Tertiary by coarse volcanic ash, remnants of which are seen in the background. Its wood was replaced with silica from the ash. Since the Pliocene uplift a stream has cut through the ash, exposing these silicified old tree stumps at the sides of the valley. (Photograph by J. L. Gillson)

Lake Florissant and Miocene life. One of the regions that are richest in specimens of the smaller forms of life of Tertiary times is at Florissant in Colorado, west of Pikes Peak. Here during the Miocene there was a small lake, five miles long by a mile wide, near which lay an explosive volcano. The ash ejected from this volcano, falling upon or washed into the lake, formed layers which covered up numerous insects and the leaves and flowers of plants. Later, lava and mud flows covered, sealed, and compressed these deposits, forming a shale that can now be split with a knife, thus revealing flattened but wonderfully preserved fossil remains. Later a stream carved a valley through the old lake deposits, exposing the shale beds along the valley sides. From this Miocene Pompeii over 1000 species of insects (Fig. 139, *h*) and 250 species of plants have already been described, and new species are being published yearly. Forms similar to those in the Old World indicate its physical union with North America, while the absence of species present in South America indicates a noncontinuous land mass in the Western Hemisphere. From these fossils we learn that there lived in the Colorado region during the Miocene several species of the tsetse fly (Glossina), now confined to the Old World, May flies (ephemerids), of which both nymphs and adults have been found, giant water bugs (belostomids), pompilid wasps, and such flower-visiting insects as bees and butterflies. About 600 species of beetles have already been described, including an abundance of weevils. Many spiders were present, and a single milliped has been described, while land snails, birds, and fishes abounded. The plants indicate a climate much more moist and mild than that of today. Around the lake flourished great redwoods and pines, figs and magnolias, together with the elm, beech, walnut, chestnut, maple, poplar, and oak. Among smaller plants were roses, grasses, ferns, mosses, liverworts, and fungi (Cockerell).

Over the rolling North American plains of the Miocene (Fig. 104) vast numbers of mammals roamed. There were dogs the size of present-day bears; entelodont pigs six feet high with formidable canine tusks and grotesque bony growths upon skull and jaws. Primitive examples of the weasel, marten, otter, and raccoon are here found for the first time. During this period there also appeared herbivorous mammals, with somewhat higher-crowned teeth, which gives evidence that the grasses had evolved to a state in which they covered the open plains in sufficient quantity to form a conspicuous source of food. Of the many species of horses living at this time some had very low-crowned teeth, as had all their ancestors, and hence must, like them, have browsed principally upon leaves and such soft food, but there were also many grazers with higher-crowned teeth. All horses had three toes, with the middle toe the longest. Some of the oreodonts (cud-chewing pigs) had by the upper Miocene likewise developed high-crowned teeth in response to this new source of food,— grasses of the open plains.

Fig. 104. View of lower Miocene beds

Gering formation, forming cliffs in the background, resting upon Oligocene (Brule) clays. In both formations occur fossil remains of animals living during those times,— primitive horses, rhinoceroses, and giant pigs. View northeast of Redington, Nebraska. (Photograph by N. H. Darton. Courtesy of the United States Geological Survey)

The Grand Canyon of the Colorado River (Fig. 105). In the magnificent vertical section of over a mile made by the waters of the Colorado River in northwestern Arizona man may read the history of this region from some of the oldest known rocks on earth to the present (Fig. 106). At the base of the present canyon by the sides of the rushing water are seen in places Archean (Archeozoic) rocks whose crystalline and contorted appearance gives evidence of the powerful forces which fashioned them. Upon these rest Algonkian (Proterozoic) red sand-

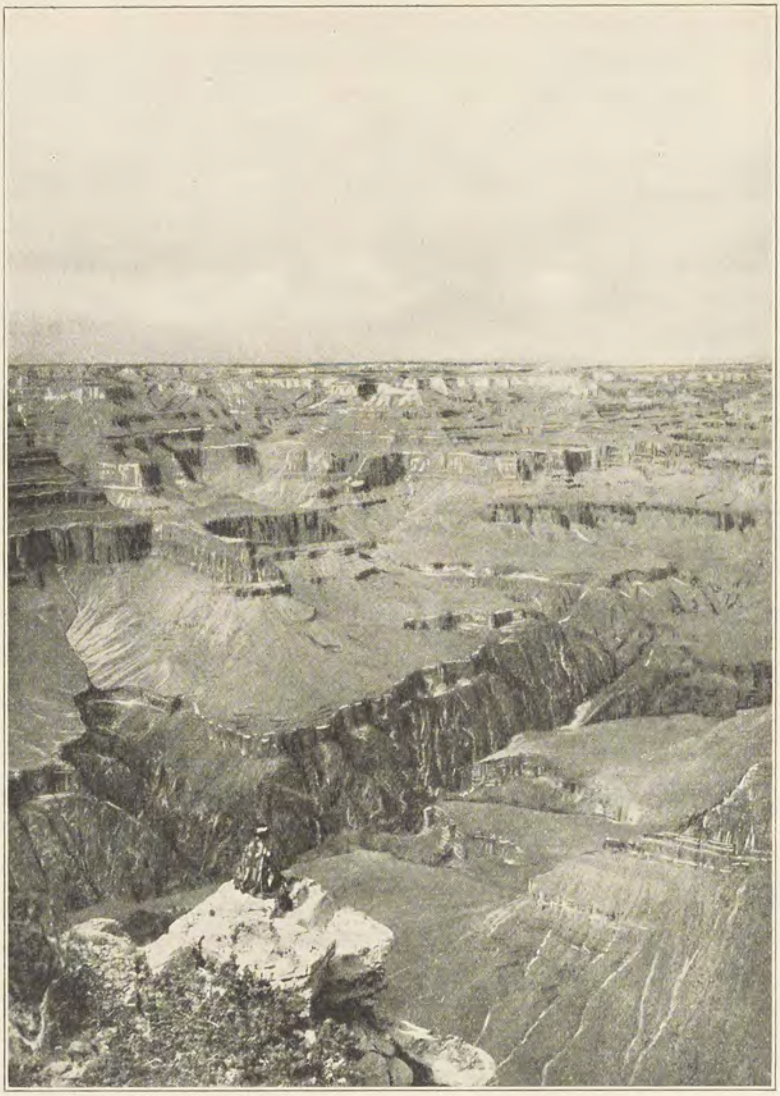


Fig. 105. The Grand Canyon of the Colorado River from near Mojave Point

View looking north at the edge of the Kaibab Plateau, showing at the base the river cutting a very narrow canyon into the hard Archeozoic granite. Above this are seen the horizontal Paleozoic sediments. (Courtesy of the United States Geological Survey) stones and shales, — evidence that hundreds of millions of years ago winds blew and rains fell upon the exposed Archean rocks as they fall today upon the exposed rocks of all subsequent ages, and that streams flowed carrying the weathered products out over delta plains. These processes continued for long ages, burying deeply the old Archean rocks in this gradually sinking region, for there are 12,000 feet of Proterozoic sediments still remaining after the tremendous erosion that occurred during the lowest Paleozoic. At the close of this Proterozoic era the region was upraised, faulted, tilted, and invaded by molten rock.

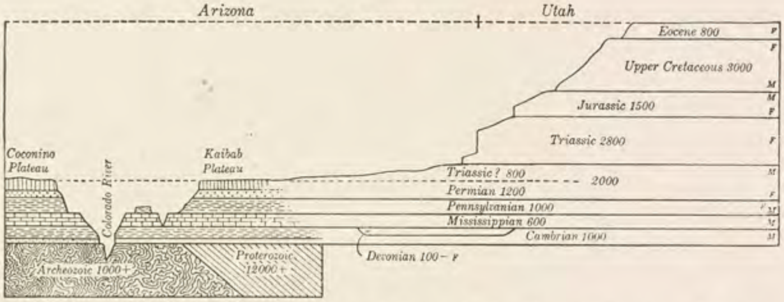


Fig. 106. Ideal section northward through the Grand Canyon of the Colorado River

The river is now cutting at a depth of about one vertical mile below the bounding plateaus and almost three miles below the surface of the upper Eocene

Then again the region was subject for a long period to the weathering and eroding forces at the surface of the earth, after which it again became a subsiding zone, this time covered with ocean waters, in which there accumulated sands and muds brought by streams from the surrounding lands and evenly distributed by tides and ocean currents. In these shallow ocean waters lived a succession of typical middle and upper Cambrian faunas, consisting largely of trilobites and brachiopods. These sought their food and lived their lives just as the crab and clam live their lives today. Again uplifted, but without tilting, the region was once more for many ages subject to erosion, for apparently it was not again covered with ocean waters until the Mississippian time, when massive marine limestones were deposited; but a few thin remnants of conglomerate and sandstone accumulated in gullies during the late Devonian give evidence of the activity of streams, and the few inclosed fossils, such as fish, appear to indicate that the deposits were laid down in fresh water. After the withdrawal of the ocean waters of the Mississippian the region was again for a time subject to erosion. In the Pennsylvanian, however, in the days when vast coal swamps covered large areas of central and eastern North America, ocean waters with their characteristic faunas flooded the western part of the Grand Canyon region for a time, while the eastern portion of it was land, for massive marine limestones in the west change into shaly limestones in the east, and farther east into continental red shales and sandstones. Again the ocean waters withdrew. During the ensuing early Permian times the low-lying region was at first comparatively moist, producing cross bedded red shales and sandstones filled with mud cracks and raindrop impressions; but later, during the deposition of the Coconino, the climate was more arid and the resultant deposits were gray-to-white sandstones, very heavily cross bedded and probably of sand-dune origin. In the later Permian very shallow ocean waters again covered this subsiding area, and the resultant siliceous limestone (Kaibab) today forms the uppermost layers of the canyon walls.

The soft shales underlying the ensuing Mesozoic deposits have eroded more rapidly than the Kaibab limestone, causing the migration of the outcrop of these and later beds far away from the canyon walls (Fig. 107). Hence the further succession of beds which formerly extended over the canyon region can best be studied by going north into southern Utah. The Triassic and Jurassic were times of semiaridity. The rains upon the higher lands, carrying the alluvial material to the lower lands, deposited it in great playas and alluvial fans. During the dry season some of this material was whipped up by the winds into huge sand dunes. Late in the Jurassic a shallow, narrow embayment (Logan Sea) from the Pacific Ocean reached far south for a short time, leaving a record of its presence in its characteristic life. It is probable that the Lower Cretaceous was wholly a time of erosion in this region, though bordering it eastward were vast fresh-water lagoons in which the accumulating sediment entombed many remains of the dinosaurs then living here. During the great inundation of medial North America during the Upper Cretaceous this region formed the westernmost area to be covered by the ocean waters. That these, however, soon moved eastward is indicated by the change of the Cretaceous deposits from marine below to fresh-water alluvial above.

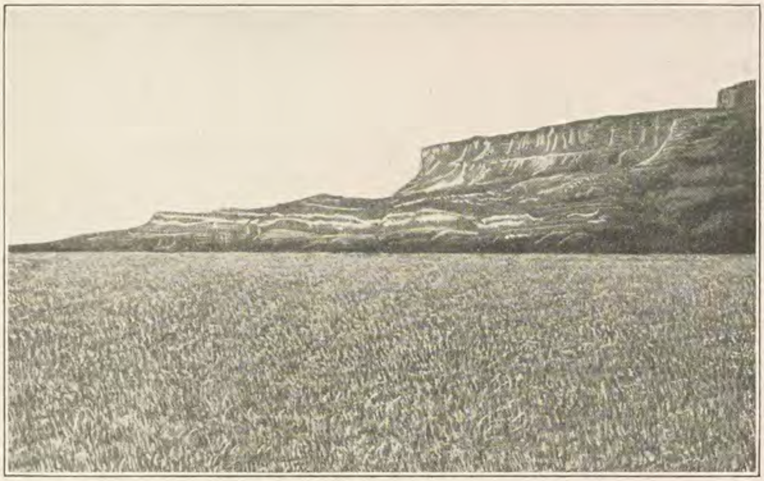


Fig. 107. View of the southeastern point of Vermilion Cliffs, Arizona

This shows the horizontal strata north of the Colorado Grand Canyon which formerly extended over it but are now eroded back to northern Arizona and southern Utah. (Photograph by H. W. Shimer)

The birth of the Rocky Mountains was followed during the early Eocene by the deposition of sediment in fresh-water lakes, containing fresh-water mussels (Unio) and gastropods.

The uprising of the Rocky Mountains was probably accompanied by the birth of the ancestral Colorado River, draining a portion of the western slope of the mountains and the region to the southwest. The Eocene plateau resulting from the general uplift of this western region was first cut by canyons which, gradually widening into ever broader valleys, reduced it finally to a broad, low plain.

During the Miocene, elevation, accompanied by north-south-trending faults, occurred, correlated with the faulting which gave rise to the caterpillar ranges of southern Nevada; by the Pliocene these elevations, in turn, through the action of weathering and of flowing water, had become reduced to a plain. During the Pliocene another uplift occurred, this time of several thousand feet, and again the river was forced to cut downward until it has produced its present sublime canyon. This most magnificent of known geological sections is now over a mile in depth (6500 feet maximum) with a width of from twelve to twenty miles. This has resulted because a comparatively large river is cutting through hard, horizontally bedded rock in an arid region, at the edge of a plateau, and has only a short distance to carry its rock débris into the deep trench of the Gulf of California. The evolution of the ancient Colorado River from a rushing canyon stream to a huge river meandering across the early Tertiary plain, and thence to the canyon of today, saw the evolution of the tiny eohippus, eleven inches high, to the horse as we know him today. This and myriads of other Cenozoic animals which quenched their thirst in the Colorado River have disappeared, but the river itself still flows on. So great a river system as that of the Colorado today is, like a great empire, the result of many territorial conquests. The force by which it conquers is derived from its fall, for by its fall it deepens its canyons and can thus extend its tributaries. The Colorado River has, however, only made a new beginning of its work. It must widen its present canyons into broad valleys, and these into a low plain, before it can rest again.

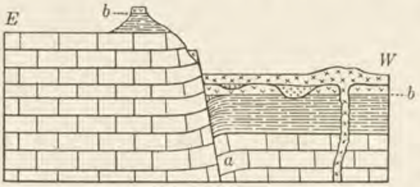


Fig. 108. East-west section through the Hurricane fault, south of Virgin River

After the region had been worn down to the plain *b-b* and widespread lavas (marked by v's) had spread over portions of it the area to the west (right) was dropped down some distance. Upon this new level, after some erosion and deposition (marked by o's), lavas flowed (marked by x's). Subsequently the western portion was again depressed to the present position. (After D. W. Johnson)

The following is a summary of the principal events in the Cenozoic history of the Colorado River region in northwestern Arizona (compare with Fig. 108). The successive uplifts of the region were nearly always accompanied by faulting and the eruption of basaltic lavas. The Eocene flexures occupied the positions of the later faults and, at least in the case of the West Kaibab fault, the lines of extensive faulting during the Proterozoic. The letters refer to Fig. 108.

TABLE XIII. SUMMARY OF THE HISTORY OF THE GRAND CANYON OF THE COLORADO RIVER

The assignment of periods is tentative

Period of great denudation	*Eocene.* Development of flexures (*a*). River young
	Oligocene. Erosion to a peneplain. River broad and meandering
	Miocene. Great faulting with uplift. River with renewed youth
	Erosion to peneplain (*b-b*) near sea level. The San Francisco Mountains were built upon this plain. River again broad and meandering
	Lava flows (marked by v's)
Canyon cycle of erosion	*Pliocene.* Renewed faulting, with uplift of from 4000 to 6000 feet, resulting in the renewed youth of the river, which began its present canyon
	Pleistocene and *Holocene.* Continued cutting of the canyon. Lava flows (marked by x's) and faulting common

Pacific coast. During the lower Tertiary the waters of the Pacific extended east to the western foot of the Sierra Nevadas and beyond the eastern margin of Puget Sound. Elsewhere the ocean lay mostly to the west of the present continental margin. In the upper Tertiary,— beginning with the mid-Miocene and continuing through the Pliocene, a probable depression of the Pacific Ocean basin caused the marginal lands with their superficial deposits to be thrust eastward, resulting in an uplift of the entire Pacific coast and the folding of such mountains as the Coast Range of the United States and the largely submerged Aleutian chain of Alaska.

Throughout the early Tertiary the Sierra Nevada Mountains had been reduced to a peneplain. In the stream channels of this plain, gold-bearing gravels had been deposited. These gravels, which were largely deposited during the Miocene, inclose bones of the rhinoceros and leaves of the fig, magnolia, and oak, indicating a warm, moist climate. Many of the deposits were later capped by lavas poured out during the latest Miocene or early Pliocene. Immediately following this the entire block of the Sierras was uplifted and tilted down to the west, forming between it and the Coast Range the present central valley of California. In the lowest depression between the deposits brought down from these two ranges flow the San Joaquin and Sacramento rivers. During the Pleistocene the common mouth of these two streams was submerged 370 feet, forming the harbor of San Francisco with its beautiful entrance, the Golden Gate.

Fig. 109. The volcano Mount Shasta in northern California
This was built up during the Pliocene and Pleistocene

Northward the Cascade Mountains, which had been folded at the close of the Jurassic and after various vicissitudes had been reduced to a peneplain across which meandered such streams as the Columbia, received another differential uplift of 8000 feet during the Pliocene, probably by faulting. This uplift was, however, sufficiently slow to enable the Columbia River to continue cutting for itself a passage through the rising mountain.

Accompanying the earth changes during the Pliocene and continuing through the Pleistocene began the growth of those great volcanoes which are today landmarks upon the Pacific coast: Mount McKinley (20,300 feet above sea level) in southeastern Alaska; Mount Rainier (Tacoma) (14,408) in the Cascade Mountains of Washington; Mount Shasta (14,380) in northern California (Fig. 109); Popocatepetl (17,882) and Orizaba (18,242) in Mexico.

THE WEST INDIES

At the close of the Cretaceous or, more probably, later in the basal Tertiary were upheaved the mountains whose summits today form the islands extending through the Windward Islands, Porto Rico, and Haiti. From the northern arm of Haiti one branch extends through southern Cuba and the Cayman Islands to Honduras at the head of the Gulf of Honduras. From the southern arm a second branch extends through Jamaica to Honduras. At the same time or a little later, probably much of the old land north and south was depressed, enlarging the geosynclines of the Gulf of Mexico and the Caribbean Sea.

The relationships of the living animals indicate that it was during the Pliocene and Pleistocene that the further faulting occurred which brought this region into approximately its present shape by a continuation of the disruption of the old land mass, portions of it being faulted down to abyssal depths (Matthew).

During the Pleistocene there was an emergence of large areas, probably due to the withdrawal of water to form the huge ice sheets; and in post-glacial times there was a resubmergence, caused probably by the return of this water to the oceans upon the melting of the glaciers (Vaughan).

SOUTH AMERICA

As was probably true of all continents, South America apparently began as a much larger land mass, which, through the persistent downsinking of the heavier ocean basins, has been reduced to its present dimensions. Guiana and southeastern Brazil are composed of pre-Cambrian rocks (granites, gneisses, quartzites) which border the ocean, so they must formerly have stretched eastward into the present ocean. For many reasons, most of which are connected with the former distribution of life, they are believed to have extended across the present Atlantic Ocean, uniting South America and Africa. Westward, South America extended to an unknown distance into the Pacific Ocean.

During the various world-wide submergences, embayments entered lower-lying lands in this enlarged South America. Thus marine beds were deposited in various places during the upper Cambrian, mid-Silurian, lower and middle Devonian, Pennsylvanian, and Permian. During the early Permian, eastern South America from near the equator to 52° south was glaciated, the ice sheets coming apparently from the east. During the Triassic this eastern region, like eastern North America, received continental red sandstone deposits. During the Lower Cretaceous occur the earliest strata which give evidence of sufficient depression of the Atlantic land mass to form in eastern Brazil a lodgment basin for nonmarine sediment. During the Upper Cretaceous this area was further depressed, thus permitting the deposition of marine deposits upon the nonmarine Lower Cretaceous.

In the western part of what is now South America a persistent sinking area originated in the Triassic. Throughout the Mesozoic this Andean geosyncline continued, mostly as a marine waterway, between the eastern old land of South America and a western, now sunken, land mass. At the close of the Cretaceous this geosyncline was elevated and folded into the Andes Mountains. During the early and mid-Tertiary the mountains were slowly eroded to a level plain, which now forms their very even sky line. This peneplain was elevated from 3000 to 7000 feet in late Tertiary, and was eroded, warped, and block faulted during the Pliocene and Pleistocene, accompanied in the west with huge igneous injections and lava flows. Late in the Pleistocene there occurred another vertical uplift of at least 8000 feet; since this time the rejuvenated streams have etched the lands to their present forms (Mather).

In South America, as in North America, the direction of mountain growth has been westward. The old lands are dominantly upon the eastern coasts. In both continents the late Cretaceous and late Tertiary mountain-making forces which produced such huge effects in the west resulted in simple plateau-like elevation in the east; since then the streams have carved the present eastern ranges.

After the Cretaceous elevation South America remained united with North America until early in the Eocene, permitting the southward migration of many northern mammals. It then became separated and probably remained distinct until early Pliocene. During this interim it developed its peculiar mammalian fauna.

EUROPE

Throughout geological history the Finland-Scandinavia region of northwestern Europe has always been the most persistently, though slowly, rising portion of the continent. Upon the southern and eastern edges of this ancient mass sediments gathered during the Paleozoic just as they accumulated upon the southern and western margins of the old northeastern land mass of North America. In both continents mountains were upheaved during the later Paleozoic. These mountains, trending northeast-southwest in North America and northwest-southeast in Europe, were apparently due to the same cause, the downsinking of the North Atlantic Ocean basin. Beyond these mountains, farther from the cause of the folding, in the Mississippi Valley and central Russia, the Paleozoic sediments remain horizontal. In both regions these mountains contain the rich anthracite deposits of the continents. Unlike

North America, however, there occurred in Europe during the Mesozoic and Cenozoic much local downsinking of the late Paleozoic mountains. Between such stable earth blocks as Finland-Scandinavia and central and northern Great Britain upon the north, and south-central France, central Spain, the Vosges Mountains-Black Forest, and Bohemia, in western and central Europe, the land sank. In these sinking zones accumulated great thicknesses of Mesozoic and Cenozoic sediment. Although North and South America had attained roughly their present outlines at the beginning of the Cenozoic, the continents of the Eastern Hemisphere did not assume their modern shape until the Pleistocene.

At the close of the Cretaceous the ocean waters had been largely drained from Europe, but at the same time certain changes were brought about apparently through the downsinking of the North Atlantic and Arctic Ocean basins. This sinking depressed the old land connecting Ireland and Spain, which after various changes became the English Channel and the Bay of Biscay embayments. So it came about that the formerly continuous land mass of western Europe was divided into a southwestern and a northwestern portion. The former, the Iberian mass of Spain and Portugal, was at times united with the old land mass of central France and at times with that of northwestern Africa. The northwestern land mass was continued from Great Britain through Iceland and Greenland into northern North America. To the east of the North Sea lay the Scandinavia-Finland mass, separated from the old lands of Siberia by a waterway from the Arctic along the eastern base of the Ural Mountains. Alaska and Siberia were separated during the lower Tertiary. They became united during the upper Miocene and thus remained until late Pleistocene times.

The northern Tertiary basin. As usual throughout earth history Europe was divided during the Tertiary into two basins of deposition by the old east-west-trending Vindelician land mass. The northern basin included Russia, northern Germany and northern France, Belgium, and England. The deposits in the western portion of this basin have been especially well studied.

It was here that the subdivisions of the Tertiary into the Eocene, Miocene, etc. were first made. The region lay at sea level, so that the deposits are alternately marine and nonmarine. During the folding of the Alps the western portion was divided into a northern, or London, basin and a southern, or Paris, basin by an east-west-trending anticline, the Weald. This extended through southern England and northern France,—through Hastings (England) and Boulogne (France). The Thames River now flows through the trough of the London basin.

The southern Tertiary basin, — Tethys. The southern European basin, Tethys, was an extensive sea, especially during the early Tertiary (Eocene, Oligocene). It extended from the present western Mediterranean east through southern Asia to the Pacific Ocean. The western Mediterranean was at times confluent with the Atlantic across southern Spain, north of the Sierra Nevada Mountains, and at other times across southern France to the Bay of Biscay depression. It expanded over the present mountainous region of the Alps, spreading south over northern Africa; at times it connected with the Indian Ocean over Egypt. Tethys included the present Black and Caspian seas, connecting at times broadly with the seas in Russia and western Siberia. It extended east through southern Asia, over the present mountainous region of the Himalayas and northern Burma into the Pacific. During the Eocene this sea abounded in a protozoön shell, shaped like a coin, whence its name, Nummulites. These animals were in places so prolific that great thicknesses of limestone were formed from the accumulation of their shells (Fig. 110). In Egypt this limestone was used in the building of the Great Pyramid of Gizeh.

Cenozoic mountain-building in southern Eurasia. At the close of the lower Tertiary (Oligocene) a period of intense mountain-folding and uplift was initiated throughout southern Eurasia, due to the compression of the deposits within the basin of the Tethys sea. This apparently took place because of a movement toward each other of the old northern (Eurasian) and southern (Gondwana) continents, or because of the downsinking of the European Mediterranean and the Indian Ocean. This movement, culminating during the Pliocene, resulted in elevating the shallow Tethys into high land areas, except in the west, where the Caspian and especially the abyssal Roman Mediterranean represent all the water areas that remain of the very long and broad ancient Mediterranean.

The Tertiary unrest resulted in the folding and upheaval of the mountains of northwestern Africa, of the Pyrenees, Juras, Alps, Apennines, Carpathians, Caucasus, of southern Europe, and of the Himalayas of southern Asia. The strata which during the Eocene were accumulating numberless nummulite shells beneath the sea are now at an elevation of 10,000 feet in the Alps, of 11,000 feet in the Pyrenees, and of 19,000 feet in the Himalayas; and naturally before erosion had destroyed the higher beds they must have stood at a much greater elevation. In places the folding was sufficiently intense to produce great overthrust faults. In Switzerland, for example, the Matterhorn is a mass of sedimentary rocks, bed upon bed, which has been squeezed away from its former associates and thrust far to the north, where it now stands, a stranger in a strange land, a mountain without roots. The thrusting was felt as warping even in southern England, where the London basin was formed

Fig. 110. A block of limestone from Egypt made up entirely of shells of the protozoön Nummulites

at this time. According to Heim the Alpine region before the folding had a width of from 400 to 750 miles, which is now reduced to 100 miles. The Strait of Gibraltar, separating Spain from Morocco, came into existence by downfaulting, probably in mid-Pleistocene times, when the Sicilian-Malta land bridge, which united Europe with Africa, was also depressed.

The local Tertiary basins of central Europe. *Lava flows.* The great mid-Tertiary compression was not confined to the elevation of mountains but formed also many basins and minor folds. As the Alps were uplifted a great trough developed along their northern base, which, gradually filling with the waste from the mountains, gave rise to the level plain of today extending from Lake Geneva through the great Swiss valley and Munich plains to Vienna.

Similarly formed is the Rhone valley depression at the western foot of the Alps-Jura Mountains. This valley is narrow where it is squeezed between the new mountains and the old, stable plateau of south-central France, just as the Swiss-Vienna valley narrows where it approaches the old, stable land masses of the Vosges-Black Forest and Bohemia.

Partly during the Oligocene though mostly later during the Miocene were formed such basins as that comprising the Rhine valley between Basel and Mainz, the Cologne-Bonn area, the Siebengebirge, Eifel, Neuwied-Coblenz, Vogelsberg, the basin midway between Prague and Dresden, the depressions in the central plateau of France, the London and Paris basins, and many others. The majority of these basins received only continental deposits. In all the areas cited except the London and Paris basins the depression was followed by the extrusion of basaltic lavas, which are now seen resting upon Miocene sediments.

Thick igneous extrusions are, however, not confined to the depressed basins but occur also in level plateaus, apparently at random, as in western America. They thus occur throughout western and southern Europe, southern Asia, and northern and eastern Africa. Apparently the causes effecting the melting of rocks were more active, and the joints cutting through the surface rocks of these regions were much more numerous than usual; hence a great amount of molten material could find exit through numerous vents. Such modern volcanoes as Etna and Vesuvius had their inception probably in the Pliocene.

The Rhine River and the North Sea. At the time of the folding of the Alps a north-south-trending dome formed to the north of these mountains. Later the dome collapsed, faulting along the sides. This resulted in the present Rhine valley, twenty miles wide, extending from Basel to Mainz, a distance of 200 miles. The total depression of the valley is upward of 3000 feet, and, as it was sinking, sediment (Oligocene to present) accumulated. Into this graben valley gathered much of the rainfall of central Europe. At first it poured southwestward into the valley of the Rhone. Later, probably during the later Pleistocene, it found a lower outlet across the peneplained lands to the north, and thence through the Cologne-Bonn depression into the area now the North Sea. Across these uplifted peneplained lands all the strength of the waters of the Rhine was used in downcutting. As a result the Rhine gorge has today a depth of 500 feet and a width of only 1500 feet (Fig. 111). Perched upon the edges of this gorge are the celebrated castles of the Rhine.

The North Sea originated as a shallow submergence from the Arctic, possibly at the close of the Cretaceous. During the Tertiary its southern end was alternately marine and nonmarine. At times it was connected with the ocean waters covering much of Russia, and at times with the Atlantic Ocean across southern England and northern France. During the Pliocene and early Pleistocene its southern margin covered northern Belgium and southeastern England. Into this marine embayment the streams from northwestern Germany poured their sediment. The great amount of sediment carried, and the shallow character of the North Sea, enabled the united rivers to extend the delta rapidly until, having made the Thames their tributary, they emptied their waters into the Arctic far to the northward. During the later Pleistocene herds of horses, bison, Irish elk, and reindeer, as well as elephants, rhinoceroses, and hippopotamuses, roamed across the fertile plains thus formed between England and the uplands of Belgium and the Rhine gorge region. Feeding upon these were lions, bears, wolves, hyenas, and man, whose homes were in the caves of the surrounding uplands. Many bones of these animals have been dredged from these old plains, which are now again covered by the waters of the North Sea. They have been dredged to a notable extent from the Dogger Bank in the central part of the sea (Munro). Since the resubmergence of this plain during post-glacial times the Rhine has again been at work extending the delta. The landward portion of this new delta now forms the fertile plains of the Netherlands.

Fig. 111. View of the Rhine gorge at Kaub

The Gutenfels Castle is shown at the left and the fourteenth-century building (Pfalz) on a rock in midstream. The level late Tertiary peneplain in which the gorge was cut is seen in the even sky line

Thus the English land mass was at times during the Tertiary separated from France and at other times united to it. In the Pleistocene, even during the flooding of the fertile plains between England and Belgium, it was united by way of Dover and Calais. The final submergence of this region in postglacial times brought the sea in over the outer valley of the Seine and Somme rivers, forming the English Channel, and brought the North Sea down to Belgium and France. It probably also submerged the Dover-Calais isthmus, which has since been deepened and widened by sea scour into the Dover Straits of today.

AFRICA

The medial portion of the old Gondwana continent is a plateau of old rocks, largely pre-Cambrian granites, gneisses, and schists. Aside from a few marginal embayments there are no late marine sediments except in the north. During the Cretaceous, Egypt and the Sahara were broadly submerged by shallow waters from the Mediterranean, but during the Tertiary these waters were largely confined to northern Morocco and Algeria and to the basin of the Nile. In the latter basin the sea was present during most of the Tertiary, for Eocene, Oligocene, and Miocene sediments are seen, and even marine Pliocene is present up the Nile as far as Aswan. The depression of the Red Sea, formed probably during the late Pliocene or early Pleistocene, was split in two northward by the promontory of Mount Sinai, so that two arms were formed,— a northern arm (the Gulf of Akaba-Jordan valley) and a northwestern arm (the Gulf of Suez). The filling of the latter at the Mediterranean end by Pleistocene and modern deposits necessitated the digging of the Suez Canal through these late deposits from Port Said to Suez to avoid the long sea trip around South Africa. The great rift valley of eastern Africa (p. 135) was probably formed at the same time and in the same manner as the Red Sea graben.

During the early Tertiary (Eocene and Oligocene) no true Carnivora were present in Africa, their place in the economy of nature being taken by the archaic creodonts, as their place in South America was taken by the carnivorous marsupials.

On this continent there were probably evolved during this early Tertiary time the elephants (Proboscidea), sea cows (Sirenia), Hyracoidea, and zeuglodons. Some evidence of this evolution is found in the Fayum district on the southern borders of the Libyan Desert, sixty miles southwest of Cairo. In the sea covering this region in Eocene times, an expansion of the Mediterranean, abounded the great Eocene whale (Zeuglodon), while on the shores throve the ancestral sea cow (Eosiren) and the ancestral elephant (the amphibious Mœritherium). During the succeeding Oligocene beside the streams pouring into this sea and upon the surrounding hills lived the more elephant-like Paleomastodon, a huge hyrax, and many other mammals, as well as giant tortoises and pythons, ostrich-like birds, and crocodiles.

Italy was a portion of Africa projecting northward by way of Malta and Sicily until it became superficially a part of Europe simply through the downfaulting of these southerly lands. This Malta-Sicily ridge is, however, only slightly submerged and still separates the Mediterranean into an eastern and a western basin.

ASIA

In Asia, as in the other two northern continental land masses, the principal Paleozoic and later mountains have been built to the southward of a northern pre-Cambrian land mass. Into geosynclines developed in succession about the southern side of this land mass (Angara) of northern Siberia was poured the sediment eroded from it. Later this sediment was ridged up into successive mountains. The latest of these mountains to be formed are the Himalayan and other ranges of south-central Asia and the largely submerged range running through Kamchatka, the Kurile Islands, and Japan. This latest uplift, late Cenozoic in age, has not yet terminated, as is shown by the many earthquakes in the Himalayas and the very recent rejuvenation of rivers there, as well as by the numerous earthquakes in the Japanese region.

With the gradual northward growth of the Indian Ocean depression, the portion of the Gondwana continent which lay between India and northeastern Africa sank. Thus the Arabian Sea was formed during the late Cretaceous and early Tertiary. India was thus left as an island, to be united later to Asia. As a result of this early Tertiary downsinking, occurred the great Dekkan lava flows (p. 271). Arabia was later separated from Gondwana by the downfaulting of the Red Sea in Pliocene or early Pleistocene times.

During the early Tertiary the areas occupied by the Himalayan and other mountains of late upheaval were beneath the great mediterranean (Tethys) sea, where they continued the accumulation of sediment begun in early Paleozoic. In mid-Miocene times this region was slightly uplifted, forming separate basins of deposit, while during the Pliocene occurred the great upheaval which brought into existence the Himalayan and other folded mountains, and the great plateaus of Tibet and Mongolia. The region of these plateaus was, during the Cretaceous and early Tertiary, when they were lower-lying lands, a possible evolutionary habitat of the large-brained Cenozoic mammals, whence they migrated to Europe and North America.

AUSTRALIA, EAST INDIES, AND THE ISLANDS OF THE PACIFIC

Central and western Australia is the old, stable pre-Cambrian land mass of this, at present, small continent. Several times during the Paleozoic and Mesozoic the great synclinal zones of eastern Australia and New Zealand were folded. The cause, as usually interpreted, was the downsinking of the New Zealand Sea and the Pacific Ocean to the east. Apparently the New Zealand Sea has been a persistently downsinking zone since early Paleozoic times. In common with the other continents Australia exhibited great volcanic activity during the Tertiary. There were great lava floods in eastern Australia during the Miocene. As was apparently true of other continents, Australia and New Zealand were greatly elevated (5000 ± feet) during the later Tertiary.

The curved lines of the East Indian islands are merely the summits of mountains folded during the Tertiary, probably upon the old land mass connecting Australia with Asia. The easternmost of these islands, including New Guinea, has been rather persistently connected with Australia, while the western, including Borneo, had its main connection with Asia.

The islands of the Pacific Ocean are largely arranged along northwest-southeast lines, as though the same cause that gave to the huge continent of North America the northwest-southeast trend of its west coast produced also submarine folds in the depths of the western Pacific, upon which volcanic eruptions have raised the present islands. Of these the Hawaiian group is 1500 miles long, while the Polynesian group (made up of parallel chains) has a still greater length.

The land of living fossils. As is indicated by the peculiar animal and plant life, the Australian region (Australia, New Zealand, and New Guinea) has been separated from Asia since the beginning of Eocene times and possibly earlier; for otherwise the placental mammals and other organisms developed upon the northern continents by the Eocene would have migrated hither. Isolated from the rest of the world there persisted upon this smallest of continents many forms of life which the greater competition upon the larger continents had long ago destroyed. In other words, evolution was much slower in the small Australian region, and the resultant changes were small in amount. Here is found Hatteria (Sphenodon), the only surviving representative of the typically Mesozoic order of primitive reptiles, the Rhynchocephalia. In the rivers of Queensland still lives Ceratodus, a genus of lungfish characteristic of the Triassic, while in the rivers of New South Wales lives the herring (Diplomystus), similarly characteristic of the Cretaceous. The cycad Zamia, still living in western Australia, was a representative of the flora of the earth during the Triassic. On the shores of the Australian region Cestracion (Port Jackson shark) and the bivalve Trigonia are found in abundance, maintaining here the association so characteristic of the Mesozoic. Naturally in all these cases, though the genus still survives, the species have changed. Among mammals it is only the lowest orders that here find representatives. Cut off from the highly evolved placental mammals there developed from Mesozoic forbears the peculiar monotreme and marsupial life of the region. This is the only region in which representatives of the lowest order of mammals, the egg-laying Monotremata, are found. Here too the next higher order, the Marsupialia, being the highest mammals on the continent, had an opportunity to evolve in all directions in which food and protection were obtainable. Hence some species of marsupials are herbivorous, others carnivorous; some live on the surface of the ground, others burrow within it; some live on trees, others in water.

By the late Tertiary many of the mammals and birds in the Australian region, as in the rest of the world, had attained huge proportions. In the Pliocene a marsupial (*Diprotodon australis*) was larger than any rhinoceros living today, and the but recently extinct ostrich-like bird Dinornis had a height of twelve feet.

Australia and South America are thus archaic in their animal and plant life for the same reason that the people of mountainous regions formerly retained so many ancient customs, words, and expressions, that is, because they were cut off from contact with the rest of the world.

VULCANISM DURING THE CENOZOIC

One of the most striking features of the Cenozoic was the world-wide outpouring of lavas. On every continent and on very many islands evidence of this activity is recorded. Surrounding the Pacific Ocean was the so-called "circle of fire." This circle, expressed in innumerable Cenozoic volcanoes, lava flows, and igneous intrusions, passes through western South, Central, and North America, the Aleutian Islands, thence southward through the Kurile, Japanese, and Philippine islands, Borneo, and New Zealand to Antarctica, then northward to Tierra del Fuego in South America. The "circle of fire" appears to indicate a depression of the entire Pacific Ocean basin during the Cenozoic which produced zones of weakness along which the lavas could ascend most easily. Another important volcanic zone passed through southern Eurasia along the line of the old Tethys sea, where Cenozoic uplift had resulted in similar zones of weakness. In addition to being abundant in these two major regions, volcanoes and lava flows are of almost world-wide, though scattered, distribution, except far within large continents.

Plateau-forming basalts. The most spectacular of the lava flows are the plateau-forming basalts, tremendous outpourings of very fluid lavas through long fissures. Being fluid they flowed far, forming plateaus. Some such plateau-forming lavas had poured forth during earlier earth history, as in the Lake Superior region during the uppermost Proterozoic (Keweenawan) and in eastern South America apparently during the Jurassic. Here, between the Amazon and La Plata rivers, they still cover 300,000 square miles to an average depth of 1000 feet. At no time before the Cenozoic, however, is there yet known to have occurred such a world-wide outpouring.

In central and western India lavas were extruded during late Cretaceous or early Eocene time, which finally covered 200,000 square miles to an average depth of from 2000 to 2500 feet (maximum 10,000 feet), forming the Dekkan Plateau.

In Idaho, eastern Oregon, and eastern Washington there were extruded upward of 100,000 cubic miles of basalt. It poured forth like molasses, gradually concealing the rugged topography of some 250,000 square miles to a maximum depth of 4000 feet, and in this way the Columbia River plateau was formed. This took place during a period extending from the Eocene up to a few hundred years ago.

During the Tertiary (with maximum in the Eocene) tremendous lava flows poured out upon the North Atlantic land mass, mostly as basalts and all essentially similar. Fragments of these are now found in eastern Greenland, Iceland (where the flows have continued at intervals to the present), the Hebrides, western Scotland (including the Isle of Staffa, with its Fingal's Cave), northern Ireland (with its celebrated Giants Causeway), the Orkneys, the Shetlands, the Faroes, Jan Mayen, Spitzbergen, and Franz Josef Land.

In Siberia, from the Yenisei River east to Bering Strait, and upon the Arctic islands to the north, are many basalt flows which came into existence during the Tertiary. That this volcanic activity has continued to very recent times is indicated by some small ash cones which still remain uneroded.

In Patagonia down to Tierra del Fuego Tertiary basalts have continued flowing almost to the present (H. S. Washington).

TOPICAL REVIEW

- North America
  - Eastern North America
  - Gulf of Mexico
  - Interior plains
  - Western North America
    - Great Basin. Caterpillar Ranges
    - Volcanoes
    - Lake Florissant and Miocene life
    - The Grand Canyon of the Colorado River
    - Pacific coast
- The West Indies
- South America
- Europe
  - The northern Tertiary basin
  - The southern Tertiary basin, — Tethys
  - Cenozoic mountain-building in southern Eurasia
  - The local Tertiary basins of central Europe
    - Lava flows
  - The Rhine River and the North Sea
- Africa
- Asia
- Australia, East Indies, and the islands of the Pacific
  - The land of living fossils
- Vulcanism during the Cenozoic
  - Plateau-forming basalts

CHAPTER XVI

PLEISTOCENE GLACIAL PERIOD AND ITS EFFECTS

Following the world-wide mountain-building at the close of the Tertiary, but not entirely caused by it, occurred the latest and one of the greatest of the glacial periods to which the earth has been subjected. From the map (Fig. 112) it is seen that the glaciation was largely confined to the northern regions of the land hemisphere and was accompanied merely by enlarged mountain glaciers elsewhere.

The temperature of the earth was lowered to such a degree that the permanent snow line was 4000 feet lower than it is now in the Swiss Alps, and 1500 feet lower in Venezuela, while the ocean waters were so chilled that in many places Arctic animals lived in what is today the warmer temperate zone.

Glaciers covered about 6,000,000 square miles, and it is probable that because of the water locked up in the ice, aided by the gravitative attraction of this ice, the ocean level was lowered about 200 feet (Daly).

In North America there were three main centers of ice accumulation: British Columbia (enlarged mountain glaciers), Keewatin (west of Hudson Bay), and Labrador. From these centers the ice flowed in all directions, but especially southward. As it moved it scraped off the soil, decomposed rock, and the solid rock below, carrying them outward and filling with this débris the preglacial valleys transverse to its flow. Although some of the débris has been carried hundreds of miles, most of it is of very local derivation. According to W. O. Crosby the great majority of the larger glacial bowlders in eastern Massachusetts have traveled less than half a mile from their original homes north of their present location. The smaller ones have come from greater distances. Many such glacial bowlders in eastern Massachusetts (Essex County) have been traced to bedrock in the White Mountains. In New York and Pennsylvania are many crystalline bowlders derived from southern Canada. Bowlders of a peculiar jasper conglomerate have been traced from their original home north of Lake Huron, through Michigan, Ohio, and Indiana, to Kentucky,— a distance of six hundred miles (G. F. Wright). The direction of glacial striæ, as well as the distribution of these bowlders, indicates the direction of ice movement.

There were several advances of the ice sheets, separated by warmer interglacial epochs, during which the glaciers were melted back as far as or farther than they are now. The causes producing these various glacial advances and retreats evidently gave rise to similar fluctuations in the mountain glaciers (Atwood), and naturally also in inland lakes. During its maximum extension the Pleistocene Great Salt Lake (called Lake Bonneville) had ten times its present size and was of fresh water, emptying northward into the Snake River and thence into the Pacific Ocean. The terraces formed around the shores of this lake during its various stages are well shown in the hills east of Salt Lake City.

The last glacial advance, the Wisconsin, deposited at its southern margin the conspicuous terminal moraine which forms the backbone of Long Island; continuing westward across New Jersey and northern Pennsylvania, this moraine passes along the Ohio River and thence northwestward. North of this moraine the country is characterized by a deranged preglacial drainage and a youthful topography, with knobs and kettles, swamps, lakes, and waterfalls, while to the south of it the Tertiary drainage developed gradually into that of today without the catastrophic glacial interim.

In Europe, where there were similar glacial advances and retreats, the principal center of accumulation included Norway, Sweden, and Finland. At the same time local mountain glaciers attained giant proportions.

The alternation of cold glacial with warm interglacial epochs was naturally reflected in the life of the times. During the glacial epochs reindeer flourished in southern France and musk sheep and arctic fox in the Pyrenees, while during the warm

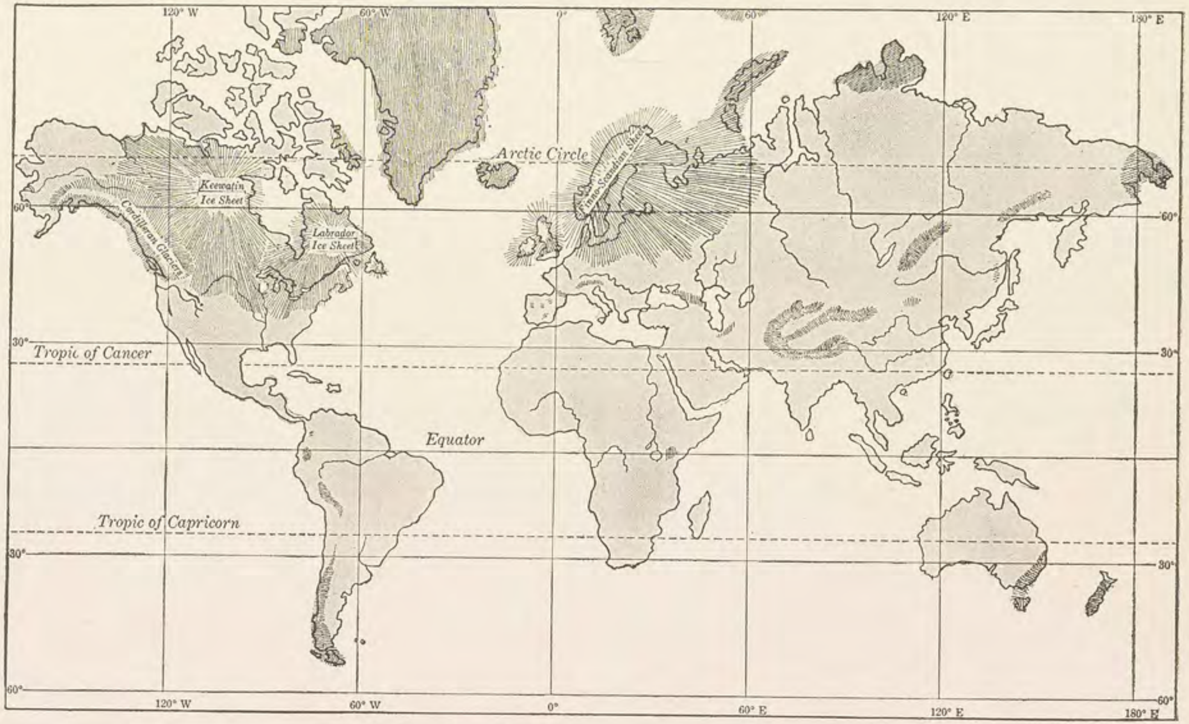


Fig. 112. Glaciers during the Pleistocene

interglacial epochs the leopard, lion, hyena, African elephant, and hippopotamus were abundant in Europe. In North America the glacial advances saw the walrus on the coast of New Jersey and musk oxen feeding in Kentucky and Arkansas.

Isostatic adjustments. The enormous additional weight to which northern North America and northwestern Europe were subjected caused them gradually to subside, so that when the glaciers melted upon the return of warmer times, the ocean waters flooded the depressed areas until the lands, deprived of their additional weight, gradually rose again. The marine deposits formed in these transgressing oceans and overlying typical glacial deposits or striated rocks are now found at varying heights, being greatest near the center of ice accumulation. For example, marine shells, whale and seal bones, etc. are found at heights about 600 feet above the present sea level at Montreal, at an elevation of about 500 feet on Lake Champlain, and about at present sea level at the mouth of the Hudson River. At this time Ottawa and Montreal were covered by normal marine waters. In northwestern Europe a similar succession of events took place.

Accompanying the sinking of the areas loaded by the continental ice masses occurred an upbulging of the lands at their margins. This took place for much the same reason that the advance of a railway embankment over a marsh depresses the portion immediately beneath and causes an upbulge at its front and sides; in other words, it is due to the elastic compression and subsurface lateral flow of the earth beneath the weight. In the case of the railway embankment the flow is of course very superficial. In eastern North America the weight of the continental glacier apparently raised the continental shelf as a low coastal plain from Newfoundland to New Jersey, across which, throughout glacial times, various species of plants migrated. Today 8 per cent of the species of Newfoundland are characteristic of the coastal plain of New Jersey and south, and do not occur in intermediate regions, the coastal plain upon which they presumably traveled having disappeared (Fernald). Across this plain the Hudson River cut a deep, now submarine, gorge. As is indicated by deep river erosion and the tilting of lake strands the southern bulge appears to have extended through southern Pennsylvania, Ohio, Indiana, and west. After the removal of the heavy ice sheets the marginal bulge gradually, though very slowly, returned toward its original position.

Fig. 113. Seasonal stratification in Pleistocene fluvio-glacial clays, Connecticut valley

The light-colored layers were laid down during summer, the darker ones during winter; the two layers deposited during one year constitute a varve. The white bands in the specimen average three-eighths inch in thickness. Counting these layers DeGeer has determined that it took 12,000 years for the glaciers to melt back from southern Sweden to the present small ice caps in north central Sweden. Antevs has reckoned 4100 years for the retreat of the glaciers from Hartford, Connecticut, to northern Vermont (St. Johnsbury)

The melting of the continental ice sheets was accompanied by the general rise of ocean levels throughout the world. The reef-building corals, which had decreased in number because of a falling ocean level and increased sediment, again increased.

Warm post-glacial epoch. During the long time that elapsed between the melting of the northern continental glaciers and a period estimated as about 1000 to 2000 B.C. the marginal lands were incised by the ocean waters, forming a more or less distinct marine terrace with such accessories as sea caves. In places, as in the British Isles, traces of Neolithic man are found in these terraces. During this minor interglacial period the ocean waters were about 2° warmer than at present (Brögger), for marine shells characteristic of Virginia today lived at least as far north as Quebec. With this warmer fauna lived man (remains of whose activity in the shape of a fish weir have been found in the Back Bay region of Boston).

Twenty-foot depression of sea level to the present. Following this slow extension of the sea, some cause, which, as Daly suggests, might have been a moderate increase of the Antarctic ice cap, appears gradually to have lowered the ocean level about 20 feet. This left the old marine terrace about 20 feet above the present sea level. (An average thickening of the Antarctic ice cap 700 feet would cause a 20-foot depression of sea level (Daly).) Traces of this 20-foot terrace appear to be world-wide; they appear in Australia, New Zealand, the Pacific islands, South, Central, and North America, and Europe.

Brögger places the completion of this relative elevation of the lands at 500 B.C.; since then, except locally and because of local factors, the ocean level has apparently remained constant. The 20-foot depression of sea level was accompanied by the cooling of ocean waters to their present temperature. This was due partly at least to the increase in the land area of the earth and perhaps partly to extended glaciers. Today, under an increased warmth, the great Arctic and Antarctic glaciers are retreating (Peary, Scott, Shackleton), and many lands are becoming more arid.

Great Lakes. The valleys formed by streams at the junction of the hard pre-Cambrian lands of northeastern North America and the softer Paleozoic rocks at their south and west were dammed by glacial deposits in various places. Thus arose the semicircle of Great Lakes from Great Bear Lake at the northwest to Lake Ontario at the southeast. The old river valley of Hudson Bay was also probably flooded at this time and remains to the present covered with very shallow ocean waters.

Similarly in Europe, upon the melting of the ice sheets, the Baltic Sea was developed at the junction between the ancient hard rocks of Norway and Sweden and the Paleozoic and more recent strata overlapping them to the south. At first it was connected not only with the North Sea but with the Arctic Ocean by way of the White Sea across Finland. Gradually, after the glaciers had disappeared, the land barriers rose to near their present position.

The many harbors on the Atlantic coast of North America and Europe are due to the fact that the amount of submergence of marginal lands since the glaciers retreated has been greater than the amount of reëlevation. On the coast of Maine the depression was from 400 to 600 feet, while the subsequent elevations averaged only 300 feet.

LIFE IN NORTH AMERICA DURING THE PLEISTOCENE AND LATER

Beginning with the expansion of the survivors of the archaic Mesozoic mammals in the Paleocene, and augmented by the Eocene migrations of large-brained modern types from the north, the mammals rapidly increased in variety and in size until their climax in the Miocene. Naturally the variety on any single continent was tremendously increased by the intermigrations permitted by the general rise of lands during the Pliocene and early Pleistocene, thus bringing about broader land connections between the continents.

During the Pleistocene, North America possessed nearly all its present wild animals, besides very many others which have either become extinct or have migrated elsewhere (Fig. 114). Among mammals there were four species of elephants,— the mastodon and three species of true elephants (Elephas). The mastodon (*Mammut americanum*), standing nine and a half feet high at the shoulder, was a forest dweller and persisted so late that it was probably known to the early Indians. It had short legs and a flattened head with low-crowned teeth topped with three or four high transverse crests. In life it is known to have been covered with long, coarse, dun-colored hair, as hair has been found with some of the skeletons. Of the true elephants the northern mammoth (*Elephas primigenius*) is best known, since it has been found with even the flesh preserved in the frozen gravels of northern Siberia. It stood nine feet at the shoulder and was clothed in a dense coat of wool beneath long coarse hair. The contents of its mouth and stomach show that it fed upon food similar to that now growing in Siberia. It ranged throughout Eurasia and North America, and was well known to Paleolithic man in Europe, as is evidenced by the lifelike carvings and cave-wall paintings of that date. The Columbian elephant (*Elephas columbi*) stood eleven feet at the shoulder, rivaling the African elephant of today. It ranged south of the preceding throughout the southern United States into Florida and the Mexican tableland. The Imperial elephant (*Elephas imperator*) was the largest species, standing thirteen and a half feet at the shoulder; it seems to have been confined to the western portion of the continent.

The hoofed mammals likewise were exceedingly abundant. Of these typically vegetable-feeding animals the horses were represented by some ten species, varying in size from pigmies to those larger than our heaviest draught horses. Some were adapted to a life on the plains only, and others to a life in the forest. These horses apparently roamed in great herds throughout North America, from Mexico to Alaska. But our modern true horse (*Equus caballus*) was not here. This horse probably evolved in Eurasia from a migrant from North America and was later introduced to the home of its ancestors by the Spaniards of the time of Columbus. The tapirs, now confined to southern Asia and Central and South America, roamed north to Pennsylvania, but were driven out of North America by the last (Wisconsin) glacial advance. Several species of peccaries, the American swine, which evolved in America, roamed north over the United States but survive today only in the limited range from Texas to Brazil. There were in addition species of camels and llamas ranging throughout North America as far north as Alaska. From the Old World came the moose (*Alces americanus*) and several species of bison, one of which, *Bison latifrons*, had a spread of horns of six and a half feet. Our living bison, the buffalo (*Bison bison*), was also present.

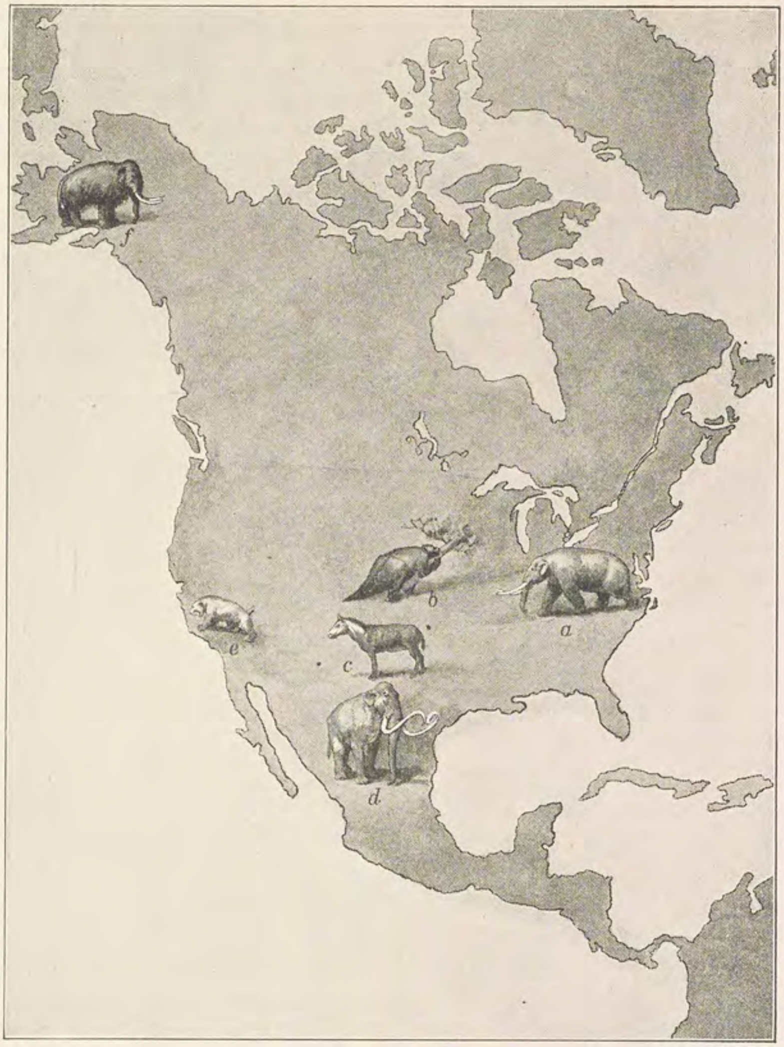


Fig. 114. Pleistocene life of North America

Only a few of the larger forms are noted: *a*, mastodon; *b*, giant ground sloth; *c*, Texas horse; *d*, Columbian elephant; *e*, saber-toothed tiger; *f*, northern mammoth. (Figures redrawn from Osborn and Scott)

Preying upon these and many other vegetable feeders, were naturally many of the Carnivora. The bear and badgers had migrated here from the Old World. Here too were such common present-day animals as the mink, weasel, marten, skunk, otter, wolverine, raccoon, fox, wolf, coyote, puma, and lynx. The king of this ancient world was, however, the now extinct saber-toothed tiger, which ranged all over the United States. It was like the leopard in height but of far heavier build, with upper canine teeth developed into great curved, saber-like tusks. The place of origin of these tigers is unknown, but they were abundant in North America from the lower Oligocene to the end of the Pleistocene.

Rodents, the order of gnawing mammals with chisel-like incisor teeth, were very numerous, and three are especially noteworthy. From South America came the capybara,— the water hog (*Hydrochœrus capybara*), the largest of living rodents, which the last glacial advance forced back into South America. From the southern continent came also the Canada porcupine (*Erethizon dorsatus*), which still remains with us. From the Old World came the now extinct giant beaver (Castoroides), one species of which (*Castoroides ohioensis*) was as large as a black bear.

South America was likewise the original home of the ground sloths, huge mammals walking upon the outer edges of their feet, which were armed with enormous claws that were of use in procuring food,— pulling down branches of trees or digging up roots. The largest of them, Megatherium, with a body as large as that of an elephant, was confined to the southern United States. Megalonyx was smaller, with a much wider geographical range, and persisted throughout the Pleistocene; it was probably hunted by early man after the close of the glacial period.

The plant life contained all our present species, aside from those that man has since brought in, and many others which have more lately died out or migrated elsewhere.

Naturally these plants and animals migrated southward and northward with the advance or retreat of the glaciers. During the interglacial epochs the mastodon fed in Alaska, while the sea cow (Manatee), now confined to Gulf waters, flourished off the coast of New Jersey. During the glacial epochs the musk ox, now confined to northern Canada, the Arctic islands, and Greenland, ranged throughout the United States south to Pennsylvania, Oklahoma, and Utah; the caribou fed in Pennsylvania and Ohio, the moose in Kentucky and Kansas, the wapiti as far south as Florida, the northern mammoth south of the Ohio and Potomac, while the range of the walrus extended to the coast of Georgia. In Georgia also grew the tamarack tree (Larix), over 400 miles south of its present limit.

Post-glacial times. The intense competition to secure food and favorable conditions for rearing young, which was caused in southern regions by the advance of the glaciers, the new enemies brought in by migration, the change from forested regions to plains and back again, and many other conditions associated with the glacial period led to the extermination of many species, especially those of large size, and to the migration of others. By the latest Pleistocene the horses had become greatly diminished, but persisted until its close, as did also the mastodon, the northern mammoth, and the saber-toothed tiger. Apparently, however, physical, floral, and faunal changes wrought by the retreat of the last (Wisconsin) ice sheet doomed even these lingerers to extinction, and North America was left with its present fauna, comparatively few in species and small of size.

Similarly throughout the world causes were at work exterminating the larger forms of life so characteristic of the Pleistocene. A few genera like the elephant, hippopotamus, rhinoceros, giraffe, tapir, ostrich, and sequoia surviving in a few places today give us some conception of the great size of many widespread Pleistocene organisms. Modern man is continuing the destruction of animals and plants all over the world. Through agriculture and the destruction of forests, through the demands for food and fur, and through industry, art, and sport, mammals and birds are rapidly disappearing. Fortunately many societies are now organized for the dissemination of knowledge leading to the protection and preservation of animal and plant life.

While it has not been definitely proved that man lived in North America during the glacial period, he was apparently here during early post-glacial times, during the late survival of some typical Pleistocene mammals. The association, in what seemed to be natural burial, of flint arrowheads, broken pottery, and charcoal with the bones of the mastodon, giant sloth (Megalonyx), and *Bison occidentalis* in various parts of North America would indicate that these extinct species lived at the same time as early man, and were hunted by him for food.

Boreal survivals in southern lands. As a result of the late glacial period many remnants of boreal floras and faunas persist in favorable localities, such as the tops of mountains or in cool swamps or glens. For, as the continental glaciers melted back and a temperate climate began to replace the Arctic cold, the plants and animals adapted to Arctic conditions would naturally follow the retreating cold. This led both northward and up the sides of mountains. Gradually, as the glaciers disappeared and warmer conditions prevailed throughout the temperate lowlands, organisms adapted to greater warmth came in. Thus it is that islands of boreal plants and animals exist today on mountain tops and in cool glens separated by hundreds of miles from their kind in the northern part of the temperate and the arctic zones. On Mount Washington in New Hampshire and on similar peaks in the east, on San Francisco Mountain in Arizona and on numerous other mountains in the west are many boreal forms. So too in the temperate lowlands in cool glens, like those at Ithaca, New York, and in swamps fed by cold springs, like those at Gracie, near Cortland, New York, northern species still persist.

Migration of birds. It is probable that migration is a habit derived from the instinctive search for favorable conditions for the rearing of young. Such conditions must include a plentiful food supply and comparative freedom from enemies. The tropical regions are densely crowded with life. Hence the birds that could travel far and that learned to take advantage of those northern lands which, because of cold or darkness, had few all-the-year residents would be most likely to rear their families and thus perpetuate their kind. Migration probably developed to some extent during the climatically rather uniform Tertiary in response to the very long winter nights, for because of the months-long nights these regions were probably much less densely populated than those farther south. The habit, however, became much extended during the glacial period (Pleistocene) and persists to the present. The northern lands are in winter intensely cold and covered with snow, but during the hot summers vast numbers of insects and seed-bearing plants appear as if by magic, furnishing ideal food for the birds. Thus migration has become an instinct which, fostered by the reproductive instinct, urges the birds north each spring; then, their families reared, the oncoming of winter again urges them to travel southward.

Because of the inclination of the earth's axis to the plane of its revolution about the sun the snow line creeps slowly farther and farther southward from the north pole for six months until near the tropics, while in the Southern Hemisphere the snow line is pushed farther and farther southward. During the other six months the process is reversed. Summer migration would, however, naturally be northward, since the Northern Hemisphere has huge land areas released from the winter cold, while the Southern Hemisphere has very little; for not only do the southern continents taper southward, but very little land extends south of the parallel of 40°.

CAUSE OF THE GLACIAL PERIOD

Cold and moisture are of equal importance in the production of glaciers. Next to the Antarctic the coldest place on earth is northeastern Siberia, yet in this dry region there was no glaciation, while the western (wet) side of the Canadian Rockies was heavily glaciated. Today, in the Andes Mountains near the equator the snow remains all summer at an altitude of 18,500 feet on the dry western side but descends to 16,000 feet on the wet eastern side. An hypothesis of glacial climates must thus account for both increased cold and moisture.

The formation during the late Tertiary of many new mountains and the general rise of the lands over the entire earth were accompanied by the union of some lands formerly separated and the separation of others. Such physiographic changes must inevitably alter the flow of ocean currents, the distribution of moisture, and the temperature of the air. To such a combination of causes appeal is usually made to partially account for the glacial period. Ellsworth Huntington has lately suggested the importance of an additional factor. It is known that the surface of the earth is cooler at times of increase of sun spots. This fact Huntington has utilized in the elaboration of his solar-cyclonic hypothesis. He postulates that an increase in the number and size of sun spots beyond present conditions might produce a lowering of the earth temperature by 9° to 11° F., an amount which meteorologists maintain would again give to North America and Europe such widely extended glaciers as prevailed during the Pleistocene. Briefly, this hypothesis postulates that the solar conditions which are manifested in a great increase in sun spots produce more intense winds on earth, which in turn carry more of the heat away from the earth's surface into the outer atmosphere, producing thus a colder earth. These stronger winds would also cause the cyclonic lows to pass through Keewatin and Labrador and northern Scandinavia instead of south of these regions, as today. Thus cold and moisture would be developed,— the two essentials of glaciers. Since, apparently, the rain-bearing winds came from the south during the later glacial period, as today, the ice fields grew in that direction until a balance was reached between winter cold and summer warmth,— in eastern North America at about 40° latitude (see Appendix, page 396).

TOPICAL REVIEW

- Pleistocene glaciation
  - Isostatic adjustments
  - Warm post-glacial epoch
  - Twenty-foot depression of sea level to the present
  - Great Lakes
- Life in North America during the Pleistocene and later
  - Post-glacial times
  - Boreal survivals in southern lands
  - Migration of birds
- Cause of the glacial period

CHAPTER XVII

SUMMARY OF EVOLUTION OF CONTINENTS AND OCEAN BASINS

The dominant cause in the evolution of land and water areas is generally considered to have been the continued downsinking of the ocean basins. According to this hypothesis the heavier earth segments underlying the oceans always tend to be drawn toward the center of the earth faster than the lighter land masses. The material underlying these basins would as a result crowd against and partly flow beneath the lands, thus raising them into mountains or plateau-like masses. This process would in turn render the marginal lands unstable and cause them to be faulted down into the basins. Such explanation would account for what appears to be a fact, that throughout earth history the continents have grown smaller and the ocean basins broader and deeper. (By *ocean basins* is meant the true oceans, not the shallow epicontinental seas that have at intervals inundated the lower-lying lands.)

Apparently until very recent geologic times the earth has been characterized by two east-west-trending continents separated by a more or less continuous mediterranean sea (Tethys). The northern of these continents (Eria) included North America and Eurasia; it more or less completely girdled the earth around the small Arctic Ocean. The southern continent (Gondwana) included South America, Africa, Arabia, India, and Australia, and extended to an unknown distance east into the Pacific, possibly, though not probably, completing the circuit to South America. These lands were, at least at times, united to Antarctica by way of Australia, South America, and perhaps Africa. The principal oceans were thus the Arctic, the North and South Pacific, the North and South Atlantic, and the Indian. According to Ruedemann the lines of folding and foliation in pre-Cambrian rocks indicate that the Tethys sea separated a northern from a southern land mass even in those distant times (Fig. 115). Many lines of evidence indicate that our present continents have arisen as a result of the increase in depth and breadth of these oceans, aided by changes in the great mediterranean Tethys.

Gondwana. The former existence of an east-west-trending southern continent has not been so definitely proved as has that of the northern continent, though the available evidence is very strongly in its favor. This evidence indicates a broad union between the Brazil-Guiana old lands and Africa, a broad land connection between Africa, India, and Australia across the Indian Ocean, and a union of Australia and South America with Antarctica.

The lower Devonian marine invertebrate fauna of Brazil and the Falkland Islands is very closely similar to that of the Bokkeveld beds of South Africa (J. M. Clarke), indicating a continuous strand line across the present South Atlantic for its migration. Broad land connections are indicated by the distribution of land plants and animals. The middle Mississippian flora of Eurasia, South Africa, Australia, and Argentina is very similar (Knowlton). The lower Permian Glossopteris flora is found in India, Australia, Antarctica, South Africa, Falkland Islands, and eastern South America; it has been found in the Northern Hemisphere only in the upper Permian of Russia. During the early Permian the fresh-water or land reptile Mesosaurus inhabited South Africa and Brazil; it has not been found in the Northern Hemisphere. The Triassic flora of South America is more akin to that of Eurasia than to that of North America.

There are many lines of evidence that indicate the existence of a strand line along the northern edge of the South America-Africa land bridge: The marine invertebrate faunas of the middle and upper Triassic of Mexico and the Mediterranean region of Europe are very similar, as are those of the lower, middle, and upper Jurassic; they differ from those farther north. The Lower Cretaceous faunas of Mexico, Central America, Colombia, and Venezuela, with the peculiar pelecy-

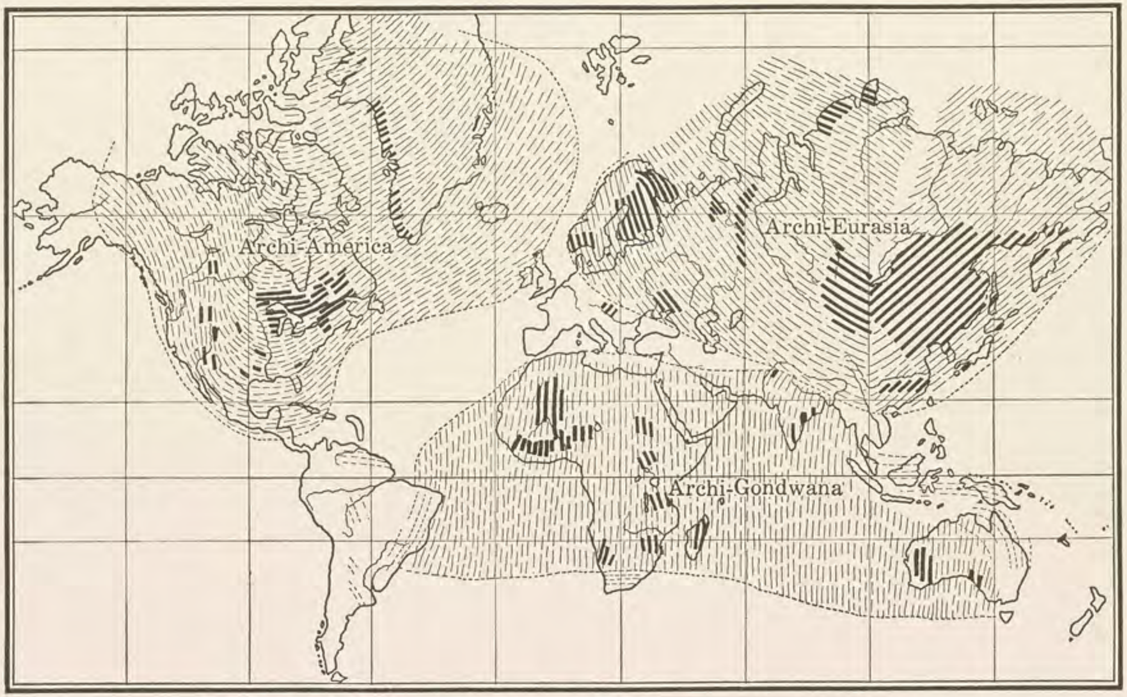


Fig. 115. Trend lines of folding and foliation in pre-Cambrian rocks

The ancient continents of America and Eurasia here shown were united into one continent, Eria, during most of the time succeeding the pre-Cambrian. Between this continent and Gondwana extended the mediterranean sea of Tethys pods, Requienia, Monopleura, etc., are like those of southern Spain and other Mediterranean lands but very different from those of the Pacific side of North America and from those of the regions farther north. So likewise the Upper Cretaceous fauna, characterized by Rudistes, Caprina, etc., of the Gulf of Mexico region is like that of Mediterranean Europe and unlike that farther north. Evidence of the gradual foundering of the South America-Africa land bridge is first seen in the Cretaceous; the earliest marine faunas on the Atlantic margins of the old lands of the continents are contained in a few Upper Cretaceous deposits of eastern Brazil and west central Africa. By the time of the Eocene such deposits have become common, indicating deeper seas, and hence, as we should expect, the Tertiary faunas of the Gulf and Mediterranean regions are distinct.

In Antarctica the floras are like those of South America or Australia during the Permian, Jurassic, Cretaceous, and early Tertiary.

Madagascar and the Seychelles far to the northeast are composed largely of pre-Cambrian granites and gneisses, as are Africa and India. They have likewise a similar north-south fold system, thus indicating a former union of these now separated land masses. Even today there are strong affinities between the faunas and floras of India, Madagascar, and Africa.

Eria. Of the former existence of the great east-west-trending continent of Eria there seems to be no doubt. Throughout the Paleozoic the marine invertebrate animals (sponges, corals, hydroids, brachiopods, bryozoans, pelecypods, gastropods, cephalopods, trilobites, etc.) of eastern North America and northwestern Europe were similar. At times this similarity amounted to identity. This indicates a land stretching across the North Atlantic, along the strand of which these animals could migrate. It indicates, moreover, an ocean sufficiently large to furnish normal marine conditions, as these animals were normal marine forms. To cite a few examples in more detail: the Cambrian faunas of New Brunswick and eastern Massachusetts were very similar to those of England and Wales, as were the Trenton (Ordovician) faunas of eastern North America to those of the Bala, or Caradoc, of England and

Wales, the Niagaran (Silurian) of Maine and New Brunswick to those of England, and the lower Devonian of Maine to those of the Coblenz district of Germany. The same comparisons hold true in the Mississippian and Pennsylvanian.

Throughout most of the Mesozoic there are no marine, shore-dwelling forms present in eastern North America for comparison, but when the record again opens in the Upper Cretaceous similar evidence again appears. The late Cretaceous fauna of New Jersey closely resembles that of northwestern Europe.

The distribution of land plants also indicates a former continuous land mass between North America and Europe. The earliest known land flora, the Archiopteris flora of the middle Devonian, flourished abundantly throughout eastern North America, Greenland, Spitzbergen, Norway, and Great Britain. It was not present in the Southern Hemisphere. The lower Pennsylvanian (Pottsville) flora of eastern North America is strikingly similar, stage by stage, to that of Asia Minor (White). The Permian flora of the Northern Hemisphere is uniform but is entirely distinct from that of the Southern Hemisphere. During the Triassic and Jurassic the similar floras of North America and Eurasia indicate continuous land, as do also those of the Lower and Upper Cretaceous and lower Tertiary.

During the Cenozoic, however, the most fully accepted evidence comes from the mammals. These appeared at the same time during the lower Tertiary in North America and Europe, but later in the southern continents. Frequent subsequent intermigrations by way of the North Atlantic land bridge until the Miocene are indicated. In the Miocene this land bridge was submerged; a contributing factor in this submergence was probably the weight of the great mass of basalts poured forth there during early and mid-Tertiary.

From the upper Miocene, through the Pliocene and early Pleistocene, migration continued by way of the Alaska-Siberia land. That this northwest land connection existed from an early period is shown by J. P. Smith in his work on the relationship of the marine, shallow-water invertebrate animals of southern and southeastern Asia and western North America for the various geological periods. When these animals are similar on the opposite sides of the North Pacific, it implies a continuous strand line along which they could migrate, that is, that the Alaska-Asia land bridge existed. When the faunas of the opposite regions become different, it implies that this bridge was broken, as it is today. The evidence for the Paleozoic is very difficult to get and has not been assembled. For the Mesozoic and Cenozoic it is as follows: During the lower Triassic the faunas were similar, in the middle Triassic different, and during the uppermost Triassic again similar. During the lower and middle Jurassic they were distinct, but were similar again during the upper Jurassic. In the early days of the Lower Cretaceous they were different, but were similar again during the latter portion of this period and all of Upper Cretaceous time until near its close, when they again became distinct. They continued thus until the Pliocene, when they were again similar and thus remained until later Pleistocene time. Similar land plants in the upper Miocene of eastern Asia and western North America indicate the existence of the land bridge at this time and likewise demonstrate the rapidity with which plants can migrate. From the upper Pleistocene to the present the faunas have again become different, indicating a cessation of intermigration between southeastern Asia and western North America, and hence that the Bering Strait had come into existence.

Tethys sea. This name, from Tethys, the sea goddess, wife of Oceanus, the ruler of oceans, was given by the Austrian geologist Suess to the great mediterranean sea which so conspicuously separated the Africa-Arabia-India land mass from the lands of Eurasia to the north. The name has been extended to include likewise the American Mediterranean,— the Caribbean Sea. Ruedemann's map (Fig. 115), showing the lines of movement in pre-Cambrian rocks, indicates that Tethys was present from earliest geologic times in both the Eastern and Western hemispheres. Since the beginning of Cambrian times it has continued to be in both of these hemispheres a more or less persistently downsinking area. For example, Europe was, throughout the Paleozoic, Mesozoic, and Cenozoic, divided into two east-west-trending deposition zones, the southern one (Tethys) being the precursor of the present Mediterranean-Caspian. This area was rather persistently united, across Spain or southern France, with the Atlantic Ocean. Thence it apparently continued westward along the northern edge of the Africa-South America land bridge into the Caribbean. This sea in turn often transgressed across the Central America region to the Pacific Ocean. In the Himalayas and in Tibet deposits of all periods during the Paleozoic, Mesozoic, and lower Cenozoic are present, most of them being marine; westward this basin appears to have been rather continuously united with the Mediterranean of Europe, and eastward with the Pacific Ocean.

The great ocean basins. The North and South Pacific, the North and South Atlantic, the Indian, and the Arctic have apparently always been oceans, and have become progressively deeper and deeper throughout earth history. Thus they have always tended to broaden their confines, with the result that they have drawn down into them the neighboring portions of the continents.

As is indicated by both the characteristics of the sediment and the included fossils, the sedimentary deposits of the various continents exhibit nothing that can be called of deep-sea origin, that is, nothing that could have been deposited at a depth greater than about 1000 feet. To this statement there are apparently very few exceptions, and these are confined to the extreme margins of the continents. On the Barbados and adjacent islands of the Windward group of the West Indies occurs a succession of sedimentary beds which can apparently be interpreted only as of deep-sea origin. These beds, from the base up, are 40 feet of calcareous (foraminiferal) ooze, 130 feet of siliceous (radiolarian) ooze (in present seas this develops at a depth of from 12,000 to 18,000 feet), 45 feet of calcareous (foraminiferal) ooze, and 25 feet of red clay. This is interpreted as indicating a sinking of this area to the globigerina (foraminiferal) ooze depth, then a further depression to the radiolarian zone, a subsequent rise into the globigerina ooze depth, followed by a sinking to the zone of the red clay; some time after this it was heaved upward to its present height. Deposits which may possibly have a similar deep-sea origin occur in the East Indies.

Since tests with the pendulum and plumb line indicate that the continents and ocean basins are in isostatic equilibrium, and that the ocean basins are underlain by material heavier than that forming the continents, it is obvious that it would require the transference of an enormous volume of light material to an ocean basin to cause it to rise into a land area, and there is neither evidence for nor explanation of such a change. But in regions of intense faulting, as in the Indies, the tremendous pressure and vulcanism might conceivably push up small earth blocks to a height of thousands of feet with comparatively slight effect upon isostasy.

There were, in all probability, no great depths in the oceans, that is, depths to which the light could not penetrate sufficiently for plant growth, earlier than the Triassic. For the animals now living at these depths are most closely related to those which evolved in shallow waters during the Mesozoic, and less closely to those of the Cenozoic. All surviving Paleozoic water-dwelling genera are today confined to shallow waters; such are the brachiopods Lingula and Rhynchonella, the mollusks Arca, Astarte, Leda, Mytilus, Capulus, Pleurotomaria, and Nautilus, and the worm Serpula. Many other typical Paleozoic orders have surviving descendants, and all are limited to shallow waters; for example, Limulus (the last representative of the Paleozoic horseshoe crabs) and the three living genera of lungfish. The majority of animals living below 6000 feet are of Mesozoic affinities, beginning with the Triassic: the family Euretidæ of the siliceous sponges, Turbinolid and other corals, the crinoid Pentacrinus, Echinus among sea urchins, etc., and the crabs Penæus, Pentacheles, etc. are well-known examples.

Throughout earth history, especially during the Archeozoic, volcanic activity has enormously increased the volume of surface waters; for it is not probable that the hydration of newly exposed rocks has withdrawn water as fast as volcanic eruption has supplied it. Thus it would appear that throughout the history of the earth the oceans have increased in amount of water, in area, and in depth, while the continents have, as a consequence, grown smaller. Yet the relation of sea level to the great interior plains of the earth has remained fairly stable, owing primarily to the increase in sediment; for erosion and deposition always tend to bring the lands and neighboring seas to sea level. Thus the interior plains, such as the Mississippi-Mackenzie plain of North America, have been repeatedly submerged by shallow seas, and during each submergence the ground surface has been raised by the addition of more sediment. If all such sediment added since the beginning of the Paleozoic were removed, the ocean would cover much of the present land surface; where Omaha, in eastern Nebraska, now stands would be an ocean upward of 1000 feet in depth.

These conclusions are illustrated in the history of the continent of North America from the beginning of the Paleozoic to the present; previous to the Paleozoic the rarity of fossils makes the record very obscure. From the characteristics of the preserved sediment, its age, and the relationship of the fossils with those of the same age in other continents, it is known that the continent extended far both east and west of its present margins and that it was united at the north with Europe and Asia until comparatively recent times. During the Triassic a series of north-south faults extending from Nova Scotia to North Carolina probably represented a tendency toward downsinking at the east, and by the Cretaceous these lands had disappeared, permitting the ocean to submerge even the margin of the present continent from southern New England southward. Finally, during the Miocene, the remaining northern portion of the land bridge to Europe was submerged.

TOPICAL REVIEW

Gondwana
Eria
Tethys sea
The great ocean basins

III

THE HISTORY OF LIFE UPON THE EARTH

CHAPTER XVIII

A HISTORY OF THE PLANT LIFE OF THE EARTH

INTRODUCTION

We have seen that the forces at the surface of the earth are constantly removing matter from some areas and piling it up in others. Many regions thus lowered are again elevated by the internal forces of the earth, and the cycle is repeated. In the organic world, however, there are no such series of similar cycles. We see life rather as evolving through a succession of countless forms, building up each for the momentary expression of the species, much as the passage of a current of electricity gives temporary form to a collection of iron filings through which it passes. From fossils (the remnants of the life of past ages) and from rocks (the hardened seashores and lake bottoms of those ancient times) we build up an incomplete conception of some of these stages of the evolution of life, as if from selected cuttings of an endless moving-picture film.

Today the lands are clothed with many kinds of grasses and adorned with myriads of different species of herbs, shrubs, and trees, while burrowing through the soil, traveling over the surface of the earth, or flitting through the air are countless animals, varying in size from very minute organisms to the huge elephant and python. The seas swarm with plants, microscopic to huge in size, freely moving or fastened to the sea bottom, from the surface of the ocean down as far as the sun's light penetrates freely; and animals are equally abundant, being found from the surface to the greatest ocean depths. Whence and how came this diversified plant and animal assemblage upon our earth? What is the sequence of cause and effect which has produced these wonderful mechanisms vibrant with that unique force called life?

While in its very broadest outlines this sequence is known, the later portion is naturally better known than the earlier because of the greater amount of evidence available. By examining the rocks laid down by the ocean and by fresh waters throughout earth history, and the remains left in them by successive generations of living organisms, it is seen that life has progressed from small, one-celled, simple forms to larger, many-celled, complex individuals and from a water habitat through an amphibious to a land habitat.

THE INCOMING OF LIFE — THE STEP FROM AN INORGANIC COLLOID TO PROTOPLASM

Any explanation of the origin of life must, of course, be very largely hypothetical. It can merely suggest a possible sequence of cause and effect from inorganic to organic, some such sequence as that which our knowledge of the orderly processes of nature assures us must have attended the first expressions of life on the earth.

It is concluded that life must have arisen in water, since protoplasm, the basis of all life, both plant and animal, is a fluid; that is, all its components are either dissolved or suspended in water, and until it had developed a protective covering such a fluid organism could not survive except in water. We may picture to ourselves as a possible habitat for the origin of this basis of all life some volcanic pools of hot water at the surface of the earth in the very early days of its history.

It is quite natural for certain chemical elements to unite into compounds that are jellylike; such compounds are called colloids. There are hundreds of such colloidal combinations forming today, and it is to be presumed there were hundreds in the past. Only one such grouping, however, became associated with life, perhaps because it alone possessed the essential elements or because its reactions were the only ones capable of being controlled by this new life force. Doubtless for a long time the jellylike masses (primitive protoplasm) that were living were scarcely distinguishable from the jellylike masses that were not living.

The assembling of the various elements to form protoplasm. This specifically vital compound, protoplasm, contains several essential elements. The great attractive powers of hydrogen and oxygen, as well as the fact that there are exceedingly few organic compounds which fail to include one or both of these elements, suggest that they were the selective agents which gradually brought in other elements, and these in turn the others now found in organisms; that in the building up of compounds, as throughout the much later development of life, natural selection was at work, preserving those elements which proved to be of greatest use. The most fundamental factor was the affinity of hydrogen for oxygen, forming water, yet with an affinity not so great but that the elements can be separated without too great difficulty. These two elements likewise unite readily with nitrogen, and one of them, oxygen, has a strong affinity for carbon (L. J. Henderson). Compounds of oxygen, hydrogen, nitrogen, and carbon were in all probability widely distributed over the young earth. They were poured out in volcanic emanations and were thus present in the hot pools of water, where, it is supposed, the earliest forms of life originated. Nitrogen in the form of ammonia was probably also derived from the air just as it is today, under the influence of lightning, and was then washed from the air by rain. With these four primary elements were likewise present sulphur from volcanic emanations and, from the decay of the igneous rocks, phosphorus, potassium, and calcium.

The incoming of the life energy. In colloids the molecules are but feebly attracted to one another, and the great amount of water renders easy the suspension of many elements between which stimulating electric actions and reactions would occur, as, for example, between metallic and nonmetallic elements. In the inorganic colloids these actions and reactions are discursive; in the organic protoplasm they are organized,—directed to definite ends. To make orderly the discursive actions and reactions of the inorganic colloid the directing energy of life was necessary in the evolution of a plant or animal body. This energy finds or develops some agent or go-between that makes all parts work together as a unit. Nerves are a very late development toward this end; but in the simplest organisms now living, which, as might be expected, are the only organisms with fossil representatives in the oldest rocks of the earth, such interacting agents are chemical in nature and are known as chemical messengers or catalyzers (in living bodies usually called enzymes and hormones).

Thus it is assumed that life first appeared in some suitable colloidal compound of several simple elements, and, as a coördinating, directing energy, built the first of the line of evolving organisms that peopled the waters of the earth and later its lands.

From its earliest beginnings in the lowest plants and animals life is associated with certain protein complexes — bodies of highly modified protoplasm — which are rich in phosphorus. These are called chromatin bodies. In the simplest of living organisms — the bacteria and blue-green algæ — they are in the form of scattered granules; in all higher plants and in animals they are gathered into one mass, the nucleus. It has been determined by experiment that the chromatin is the seat of heredity.

TABLE XIV. ILLUSTRATION OF THE ADVANCE IN THE SOURCE OF ENERGY OF EARLY ORGANISMS

The organisms here listed must be considered as merely the nearest living relatives of still more primitive types. They are arranged from simplest below to more complex above

SOURCE OF ENERGY	PROTOPLASM	PROBABLE EARLIEST APPEARANCE	ORGANISM
Sun's rays acting through chlorophyll	With a distinct nucleus	Archeozoic	Green algæ
Sun's rays acting through phycocyanin	With the beginning of a nucleus	Archeozoic	Blue-green algæ
Oxidation of inorganic substances	Without a nucleus	Archeozoic	Nitrifying bacteria

Sources of energy. In order that life may continue, a continuous supply of energy must be furnished to the colloidal protoplasm. The only apparent sources of this upon earth are the sun's rays and the energy released through the oxidation of inorganic substances. The latter source is today comparatively unimportant. The vast majority of organisms use the kinetic energy of the sun's rays to break up the inorganic compounds, especially carbon dioxide, into their separate elements and then recombine them into the potential energy of organic foodstuffs. This foodstuff then forms a reservoir capable of being drawn upon by either plants or animals for growth, reproduction, and motion.

PLANT-ANIMALS — THE EARLIEST EARTH LIFE

Oxidation of inorganic substances. Nitrifying bacteria. Judging by the forms of life persisting to the present, one of the earliest sources of energy was that due to oxidation, the energy released by the union of oxygen with various substances. Such oxidations are hastened by the presence of heat. There are upon earth today certain very primitive plants, the so-called "primitive feeders,"— the prototrophic division of the bacteria, — which derive their energy from the oxidation of inorganic matter and are thus independent of sunlight and organic food.

That the earliest forms of earth life were similar to such living simple bacteria is further indicated by the very simple structure of all bacteria. The body is one-celled, with a watery granular protoplasm, the chromatin hardly differentiated, surrounded by a delicate membrane or at times naked, multiplying by simple division, capable of withstanding extremes of heat. That the bacteria are exceedingly ancient forms of life is indicated not only by this extreme simplicity of body and of reaction to environment but by the presence of fossil bacteria in the Proterozoic rocks (Walcott, Gruner).

Sun's rays acting through phycocyanin. Blue-green algæ. As we look upon the all but universally green world of vegetation today it becomes apparent that in the green coloring-matter (the chlorophyll) life has found the easiest medium for transforming the sun's rays into available energy. There is some evidence, however, that the earliest life tried other chemical compounds. Some of the sulphur bacteria possess a red pigment that decomposes carbon dioxide and may represent a pre-chlorophyll stage in the utilization of the sun's energy. The blue pigment in the blue-green algæ may likewise represent an earlier stage than the green chlorophyll, though in the blue-green algæ both blue and green coloring-matter are present, and it may be that a combination was the principal transitional stage to the common and now almost universal green chlorophyll. It may have taken life ages to effect the union between magnesium and iron with some hydrogen-carbon compound, forming chlorophyll, that made possible the use of the sun's energy. The blue-green algæ may with much probability be taken as representative of early life conditions, since they, like the bacteria, possess such primitive characters as (1) indistinct differentiation of the nucleus from the rest of the protoplasm; (2) ability to withstand heated waters; (3) reproduction by simple division; and (4) formation of gelatinous colonies. They represent an advance upon the bacteria, however, in the possession of a more definite nucleus, in the ability to utilize the sun's rays as a source of energy, and in having some forms that are transitional from a unicellular to a multicellular stage of development. In some species the usually simple cells are joined in hairlike rows which branch and have cells performing slightly varying functions.

Summary of origin of living forms and geological evidence (Table XIV). It is thus supposed, from a consideration of such primitive present-day forms of life as the bacteria and blue-green algæ, that the earliest living forms on earth were small, jellylike masses of protoplasm, born in volcanic pools during the early Archeozoic, in water whose warmth stimulated to greater activity the interactions taking place within this primitive colloid. Through the energy derived from the oxidation of inorganic compounds they increased in size and also in number by subdivision. That the water in which these early forms originated was quite warm if not even hot appears to be suggested by the following considerations: both bacteria and the blue-green algæ, the two most primitive orders of organisms now existing, include many species that thrive in hot volcanic waters, an ability practically absent from higher organic groups. As is well known, rising temperatures increase the activities of protoplasm from the point where it is solid (that is, freezes), 0° C., up to a temperature at which its maximum activities occur. With increase of heat above this optimum the protoplasm decreases in activity until it coagulates and death ensues. In the more highly evolved grass-green algæ death follows at a temperature of about 43° C., in many of the blue-green algæ death results at about 73° C., and many bacteria live in water of 89° C. Besides being heat-loving, bacteria are light-avoiding.

The very limited geological evidence tends to support the above outline of the early evolution of plants, which has been derived mainly from structural and embryological sources. In the earliest of the five eras of earth history, the Archeozoic, there is evidence of an abundance of life in the great amount of carbon preserved in the water-laid strata of those times. Today the principal source of carbon at the earth's surface is plant and animal life; it was presumably the chief source also during the Archeozoic. An abundance of graphite occurs throughout the world in the quartz schists of the Archeozoic. In the Adirondack Mountains are alternating beds of graphitic schists from 3 to 13 feet thick, which give the appearance of fossil coal beds. The dead organisms of those Archeozoic times, probably mostly algæ, would sink to the bottom of the water in which they lived and, in the absence of bottom-dwelling scavengers, would partly decay. Their remains would accumulate in the form of carbon and would thus be preserved when the mud into which they fell hardened later into limestone and shale, now metamorphosed into marble and schist. The amount of carbon in the sedimentary rocks of the Proterozoic is enormous. It is estimated that the carbon contained in the dark shales of the Animikean formation, extending from Michigan to Minnesota and far into Canada, would, if concentrated, make a bed of anthracite coal 200 feet thick. In addition to graphite and the carbon particles giving the dark color to sediments, real plant fossils — microscopic blue-green algæ — have been reported from the Archeozoic (Gruner).

Sun's rays acting through chlorophyll. Flagellates. As a next step, forms evolved possessing a distinct nucleus and capable of utilizing green chlorophyll alone. At the same time freedom of motion increased: the flagellates, of which Euglena is an example, are free-swimming. In this group the characteristic of activity became so emphasized that for the first time in the history of life we may distinguish animal and plant characters. The flagellates possessed such animal characters as active locomotion, amœboid movements, contractile vacuoles, and red pigment spots, and such plant characters as green chlorophyll and thick-walled resting spores.

The primitive flagellates thus represent the survival of a group which was sufficiently generalized, that is, included enough differing characteristics, to give rise to widely varying groups. It is supposed that from the flagellates arose (1) the one-celled aquatic animals, the Protozoa, through the loss of green chlorophyll and the consequent necessity of greater freedom of movement for the acquirement of food, and through the loss of the more complex nucleus; (2) in another direction, the one-celled aquatic and terrestrial grass-green plants, the Protococcales (algæ which developed more chlorophyll and hence gradually lost some of the freedom of movement); and (3) the slime fungi, the Myxomycetes, through the acquisition of a land habitat.

TRUE PLANTS, AQUATIC AND AMPHIBIOUS

One-celled green algæ. The Protococcales are fresh-water or land dwellers. Many resemble the flagellates in form, in method of reproduction and movement, and in swimming freely by cilia or flagella; others are fixed by their gelatinous walls to rocks in water or in damp, shaded places on land. An example of the sessile kind is Pleurococcus, which forms bright green coatings on old shaded tree trunks.

Many-celled green algæ. In some of the one-celled grass-green algæ, such as Pleurococcus, the new cells remain for a time in contact. Gradually there evolved forms in which the new cells no longer separated to live apart as new individuals, but clung together, forming one many-celled individual. If the cells remain in contact end to end, the result is such a filamentous alga as the common fresh-water Spirogyra, or Ulothrix. If the cells remain in contact in a plane, a flat expansion results, like the sea lettuce, Ulva (in this, however, the cells are double).

Chlorophyll is present in all the algæ, although in one class it is marked by brown pigment, in another by red. The brown algæ (Fig. 116) apparently evolved in adaptation to those habitats which were alternately exposed and covered by the tide, and the red algæ, below low tide, in response to the different character of the sun's rays which penetrate to this depth. These classes are most abundant at the designated depths but vary considerably.

Certain of the algæ, tending to live more and more upon living or dead organisms, yielding to the easy life of a parasite or saprophyte, developed into the present-day fungi.

The first great step upon land — primitive bryophytes. With both fresh and ocean waters of the young earth inhabited by plant life, there still remained the swamps and the dry lands; these were unconquered possibly by any plants higher than the bacteria.

Early fresh-water lakes were doubtless subject, at least upon their edges, to annual droughts, as are the lakes of today. At times, when the margin of the lake became reduced to a swamp and this to a damp soil, there would be a tendency in plastic types of algæ for new cells to extend themselves downward from the under side of the thallus into the soil to secure a maximum amount of moisture, very much as root hairs grow in the higher plants today. The plant would also get some of its nourishment through these newly formed rootlets.

The cells above, in contact with the air and light, developed a more resistant surface layer of cells, the cuticle, as a protection against the drying air. The entirely submerged primitive plant took not only its food but also its air through the whole plant, for, being under water, it needed no protection to keep it from drying up; but as soon as a plant began to live outside the water, its surface had to develop a protection against the drying out of the tissues, which in turn necessitated the development of food-procuring organs, the rootlets, and a breathing apparatus, the stomata. In algæ the entire plant is held upright by the water. The development of cuticle and more rigid cells enabled the bryophyte to support a little of its own weight, most of which, however, still rested upon the ground or water. The lower cells in contact with the earth would, under gravity, tend to be used for storage and would, because of the darkness, fail to develop chlorophyll. That the earliest wet soil plants consisted, in large part at least, of such alga-like, flat, green expansions, possessing such characteristics as are outlined above, is indicated by the embryology of our more primitive living land plants, from liverworts through ferns to club mosses.

At times of swamp expansion male and female cells, the gametes, could unite, but not during times of drought. The asexual spores, however, could be developed and best scattered under dry conditions. So it is supposed that under the influence of such climatic conditions the generation producing gametes would be forced to the wet season and the spore-producing generation to the dry season. This hypothesis apparently finds verification in the growth of the various living species of bryophytes and pteridophytes (see page 310).

The bryophytes apparently evolved under the impetus of some such climatic changes. According to this view living liverworts and mosses represent a survival of the general type of the first land forms which evolved from the algæ. In the liverworts there is as yet no distinction of root, stem, and leaves. In place of roots there are scattered minute rootlets covering the under surface of a large portion of the plant. That liverworts are imperfectly adapted to land conditions is likewise shown by the fact that the entire plant often assists in the absorption of water and mineral substances. It is thus forced to a shady and damp habitat. Since the very small rootlets are too short to get the deeper-lying moisture, and since the lack of a vascular system makes the tissue too weak to support a great weight, and since, moreover, reproduction needs external water for the union of the gametes, the liverworts must remain small and close to the ground. They have in all probability never been taller than they are now.

Geological evidences as to the great antiquity of the bryophytes. (1) In the early Devonian, at Rhynie in Scotland, occur a series of silicified peat beds. In these beds, along with algæ and fungi, occur many plants — Rhynia, Hornea, etc.— which are interpreted as bryophytes having strong affinities with algæ on one side and with ferns on the other. They are the simplest of known vascular plants, growing to a height of eight inches from creeping underground stems. They have no leaves or differentiated roots; on the ends of the narrow, thallus-like branches are spore sacs. (2) Such liverworts as Riccia and Marchantia are found at present all over the world. Now liverwort spores, being green, cannot survive to be carried far. There were, for example, no liverworts on Krakatoa twenty-three years after the sterilizing volcanic eruption, though they were carefully searched for; yet they are abundant twelve miles to the southeast in Java and likewise to the north in Sumatra. Hence, to account for their present world-wide distribution, they must be of very ancient origin. (3) There are other grounds for supposing that the earliest of land plants originated in the transition period between the Archeozoic and the Proterozoic. The Archeozoic contains almost no pure quartz sandstone, while the Proterozoic throughout contains an abundance of such sandstone and mud rocks. Pure beds of quartz sand imply that the surface of the earth supplying it was held from washing until the rock had been maturely weathered. A protective covering of vegetation is thus suggested for at least the more moist regions.

The second great step in the development of a land flora — the ferns. Because the sun shines and the winds blow, causing rains, life that was born in water and that, because of its high water content, needs a frequent renewal of water for its continued existence, can spread away from the swamps and over the drier lands. Hence the next great forward step in the evolution of a land flora was naturally the acquirement of roots by the sporophyte (see page 310) for the utilization of such temporary supplies of water as the rain brings. Urged, doubtless, by times of drought, probably during the lower Paleozoic, the developing gametospore in some forms of bryophytes, instead of merely sending an absorbing foot downward into the tissues of the gametophyte (see Fig. 116), as it does in the bryophytes, sent it still farther down into the rich soil beneath. Contact with the very different environment of the soil, together with the more continuous and abundant food supply which was furnished through the better absorptive powers of the roots, probably acted as a stimulus in the development of a larger aërial portion — stem and leaves. In most algæ the sporophyte was entirely dependent upon the gametophyte; in bryophytes it could get its own carbon and oxygen from the air, but for other essential food it was dependent upon the gametophyte; finally, in the ferns, because of the development of roots, it could provide in addition its own water and earth substances. It thus became self-supporting, and has remained independent through all its later development in the higher plants (Fig. 116). The root enabled it to utilize the drier season for growth, and since it need not remain close to the soil, as does the gametophyte, in order to permit the union of the gametes, it rapidly became the larger and longer-lived plant, and the principal generation for photosynthesis, while the gametophyte became correspondingly small and short-lived. The result was the fern.

That this was in brief the geological history of the ferns seems to be indicated by the life history of the ferns of today.

Life history of an amphibious plant, the fern. In the fern the water stage, the prothallus (Fig. 116), is a green expansion with many scattered rootlets upon its under surface. It can live only in damp places. Upon its under surface grow male and female organs which, upon maturing, can open only through the expansion caused by external water, such water as, given by a rain storm, fills the space between the soil and prothallus. At this time the male cell, swimming through the water to the female, unites with it, and this united cell, growing for a time upon the prothallus, soon forms a green expansion, a leaflet above and a rootlet below. It has now become the land stage, the sporophyte, the familiar self-supporting fern plant, and the minute prothallus dries up. Not only may this fern now grow without much water, but relatively dry air, such as is normally prevalent in late summer, is usually necessary for the bursting of the spore case and the liberation of the spores. These spores cannot grow during the following spring without an abundance of moisture. This necessary alternation of wet and dry habitats in the case of the fern appears to point to some such ancestral stimulus as the annual drying up of fresh-water swamps.

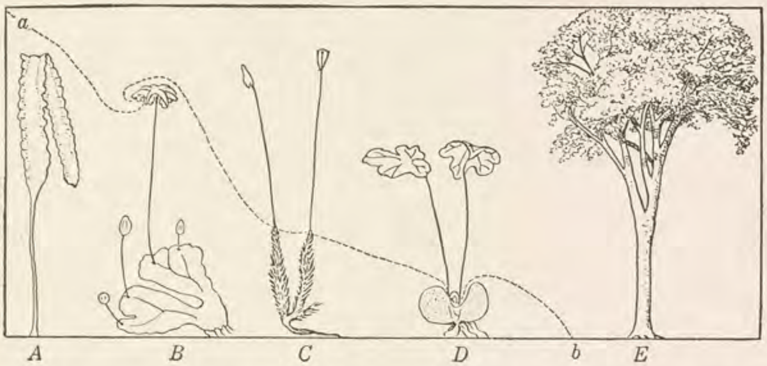


Fig. 116. Diagram showing the increase in prominence of the sporophyte stage of plant life from the algæ to the higher seed plants

The gametophyte stage of the various forms is below the line *a–b*, the sporophyte stage above it. The size of the plants in the diagram bears no relation to their size in nature. *A*, the marine alga *Laminaria saccharina*, called the devil's apron; *B*, the very common liverwort *Marchantia polymorpha*; *C*, the hair-cap moss *Polytrichum commune*; *D*, a very young sensitive fern, *Onoclea sensibilis*; *E*, the elm tree, *Ulmus americanus*. Among the bryophytes (*B* and *C*) the gametophyte is the prominent stage. This is the common liverwort or moss plant which bears the sporophyte; this latter remains attached to and dependent upon the gametophyte throughout its whole existence. In the pteridophytes (*D*) the sporophyte is the prominent, common, leafy fern plant which has become independent of the gametophyte; the latter is the two-lobed prothallus which, though independent of the sporophyte, is tiny and short-lived. In the spermatophytes (*E*) the gametophyte stage has become so reduced that its whole existence is passed invisibly, within and dependent upon the sporophyte. (See Fig. 120.) (Courtesy of The Macmillan Company)

The development of a vascular structure. A further profound change in structure opened to plants wider possibilities in variation. Algæ, bryophytes, and the gametophyte generation of all higher plants have a cellular structure in which the water and manufactured food move from cell to cell irregularly as through a swamp. Accompanying the evolution of roots, the land generation — the sporophyte — develops a vascular structure; that is, certain cells become more elongated and are placed end to end, forming vascular ducts, thus enabling the water from the roots and food from the leaves to flow somewhat as through pipes and hence faster and farther. The result is the development of stems and long leaves. Thus the vascular system made possible larger plant bodies, just as the bones and blood-circulatory vessels make larger animal bodies possible. The Rhyniaceæ from the early Devonian of Scotland — bryophytes with fern and club-moss tendencies — are the simplest of vascular plants.

Fossil ferns. Throughout the middle and upper Paleozoic the majority of plants had fernlike foliage. Accordingly they were called ferns until it was found that many reproduced by seeds instead of by spores. The majority of these forms have been found to possess seeds and are hence called seed-ferns, but there are a very great number that probably were true ferns. Though it is almost impossible to distinguish in fossil forms between the sporangia of a fern and the pollen sacs of a seed-fern, yet the general appearance of the plants and the detailed structure of the stem are different from the known seed-ferns and very like the living families of ferns. It thus appears probable that, branching from the archaic, primitive ferns of the earlier Paleozoic, there appeared several families of true ferns. Of these one of the most primitive is the Osmunda family, represented among others today by the royal fern, and with known representatives from at least the Permian to the present. Its ancient origin is corroborated by its delicate green spores, a characteristic of the liverworts. The dominant family in the upper Paleozoic was the Marattiaceæ, a family living today mostly in the tropics, very highly organized in both vegetative and reproductive structure. Throughout the upper Paleozoic these were tree-ferns up to sixty feet in height, with an anatomy more elaborate than that of living forms but of the same type; they extended apparently to all parts of the world. These are so closely related to the seed-ferns that it is evident that they have had a similar ancestry. The family has left fossil representatives much like the living genera Marattia and Danæa from the Triassic to the present. Accompanying these two families of ferns in the upper Paleozoic was a great abundance of other ferns, usually of simple organization, from which probably arose most of our living ferns. The majority of the living families of ferns can be definitely traced well back into the Mesozoic.

From the Paleozoic to the present, ferns have included both small ferns and tree-ferns; thus, unlike the horsetails and club mosses, they have suffered no universal reduction in size.

Equisetales, the horsetails. Another order of plants which had numerous representatives in the Paleozoic was the Equisetales, commonly called horsetails (from their method of branching) or scouring-rushes (from the great amount of silica present). Judging from both living and fossil examples, they probably evolved from the same stock as the ferns, for the most primitive stage of the horsetails, the green prothallus, is very similar to the prothallus of the ferns in its organs of reproduction. While the gametophyte generation is thus basically similar to that of the fern, the later-developed sporophyte is very different. Since in the horsetail the latter generation evolved in the direction of large-jointed stems instead of larger leaves, as in ferns, many of the plants rapidly attained to the stature of trees. This thickening of stem, however, brought about the addition of more and more vascular strands, so that the plant became in this respect a tree like a gymnosperm or a dicotyledon, with its broad zone of secondary wood, traversed by medullary rays, separated from the bark by the growing cambium (Scott). This type of plant evolved in the late Silurian if not earlier. Throughout the upper Paleozoic the most characteristic genus was Calamites (*calamus,* a reed). Its roots had the characteristic large air spaces of water or wet-soil plants. Like most ferns, horsetails had creeping underground stems, from which arose the pith-filled, furrowed, and many-jointed stems, with leaves and branches also at the joints. In Calamites the narrow leaves, often several inches in length, were separate or united at the base only, while the roots sprang directly from the stem, and like it produced abundant secondary wood.

The Paleozoic tree horsetails (*Calamites*). Though extending from the Devonian to the Permian, the Paleozoic tree horsetails were especially abundant in the coal swamps of the Pennsylvanian (Fig. 117). The fossils usually occur in the form of mud or sand casts of the pith interior. They were tree-like in stature, reaching a maximum height of 90 feet and a diameter of at least 15 inches. The ancestral Calamites from the Devonian and the Mississippian, such as Archeocalamites, Pseudobornia, and Protocalamites, are characterized by simpler cones and by much-divided, fernlike leaves. The world-wide upheaval of mountains at the close of the Paleozoic, with its accompanying glaciers and deserts, seems to have killed off these tree horsetails with their specialized development; for the lower and middle Mesozoic horsetails, mostly Equisetites, have the leaves usually united into a sheath, as in the living horsetails, and also simple cones, with spores of one size. Throughout the Mesozoic the horsetails continued changing; since then they have been closely akin to modern Equisetum. Thus our modern horsetails are seen to be the degenerate survivors of a once mighty race of plants which aided in the formation of the huge coal swamp forests of the upper Paleozoic. The degeneracy started by the upper Paleo-

Fig. 117. The Pennsylvanian tree horsetail, Calamites, and the modern common horsetail, *Equisetum arvense*

zoic earth revolution was continued throughout the Mesozoic until there resulted the usually small (from one to four feet high), herblike horsetail of today, with its very simple structure. Its usual habitat is shallow ponds and swamps, as it apparently was in the days of its huge Paleozoic ancestors; but today some species have adapted themselves to drier soils. Of many genera throughout the past there remains today only the single genus Equisetum, with some twenty-five species (Fig. 117). It is thus seen that the horsetails are not only degenerate but are tending toward extinction.

Lycopodiales, the club mosses (Figs. 118, 137, *h*). The fourth type of plant which, it is supposed, evolved from the primitive bryophytes was the Lycopodiales. The name *club moss* is derived from the clublike cones of some species and the small, mosslike leaves. The gametophyte of Lycopodium, a living genus with simple characters, is thick, ending in green, leaflike lobes (recalling the liverworts) in which the sex organs are produced. While the gametophyte of the club moss is thus reminiscent of the liverworts, and while the later-evolved sporophyte shows its cousinly relationship to the ferns and horsetails, it evolved a type that is very distinct. It is similar to the horsetail in the enlargement of the stem but without its joints. This type probably evolved in the mid-Paleozoic open fresh-water swamps, and was throughout the upper Paleozoic represented both by herblike forms and by tall trees.

Of the tree club mosses hundreds of species have been described from the upper Paleozoic; they evidently formed the chief feature of the huge coal swamps of the Carboniferous. Their two chief genera are Lepidodendron (Greek *lepis*, scale, and *dendron*, tree) and Sigillaria (Latin *sigillum*, seal), each receiving its name from the conspicuous scars left at the fall of their leaves. Lepidodendron frequently attained a height of 100 feet.

In both Lepidodendron and Sigillaria the leaves are grasslike, long, and narrow, frequently half an inch wide at the base and from 4 to 7 inches long. In some species of Sigillaria they attained a length of 3 feet. On the upper surface near the base of each leaf is a tongue-shaped outgrowth, the ligule, just as in the living club mosses Selaginella and Isoetes.

On the under side each leaf bears two furrows in which are the minute breathing pores, the stomata, for the extraction of carbon from the atmosphere. The furrows are partly concealed by minute hairs. Plants with few and hidden stomata are today characteristic of dry climates and salt marshes, but it seems more probable that these Paleozoic plants lived in rather open swamps. The leaves soon fell off and are hence found preserved in place only upon the twigs. Lepidodendron has its leaves arranged spirally around the stem, while in Sigillaria they are arranged in vertical rows (Fig. 118).

Fig. 118. Club mosses

The fossil club moss Sigillaria (one foot in diameter), abundant throughout the world during the Carboniferous time, and the modern club moss Lycopodium. Upon the latter there is a single spore-bearing club at the top; this gives the common name to the group

Underground stems of both genera, ordinarily called roots, are quite similar and were named stigmaria in reference to the circular scars, or stigmata, left by the easily separated rootlets. Each rootlet, often a foot in length, though round and serving to extract food and water from the soil, was more like a leaf in its vascular system. From the base of the trunk four of these great stems, with the structure of the trunk, diverged horizontally through the soil, forking as they went. One underground stem measured over 37 feet in length and had a diameter at the base of the tree of 2 feet 8 inches.

The tree club mosses did not survive the earth revolution of the uppermost Paleozoic, though some may have persisted as greatly stunted forms; for the Triassic Pleuromeia of Europe, a plant three feet high, looks much like a very small Sigillaria and so may possibly be transitional to the Cretaceous, Tertiary, and living Isoetes (Scott). The other living heterosporous club moss, Selaginella, can be traced into the Paleozoic in forms as small as those of today. The fossil forms are called Selaginellites, but are scarcely distinguishable from the living forms. Thus, though the club mosses, as an order, show very great degeneracy, both as to structure and as to size, they still persist in four genera and some seven hundred species, holding their own as relatively inconspicuous forms beneath the shade of later-evolved plants or upon the edges of swamps.

Summary of evolution of the pteridophytes. A common origin for all types of the pteridophytes — ferns, horsetails, sphenophylls, and club mosses — from some primitive bryophyte is indicated by the following characteristics which they possess in common: (1) the reproductive organs and the germination of the gametospore are suggestive of the liverworts (Curtis); (2) both the gametophyte and the sporophyte generations are self-supporting and hence are confined to comparatively moist places; (3) all possess underground stems from which arise both rootlets for the extraction of food and water from the soil and the green aërial portion for the absorption of carbon from the air; and (4) the vegetative and reproductive leaves are very similar in appearance.

TRUE LAND PLANTS

The earliest true land plants — the Cycadofilicales, or the seed-bearing ferns. From some very old fernlike type there evolved, mainly during the middle Paleozoic, types of plants with the most varied capabilities the world had yet seen,— plants with very fernlike foliage but bearing naked seeds, and therefore true gymnosperms; and under the variable stresses of earth changes, from somewhere within or near this old seed-fern complex, arose the higher plants of today. In this type for the first time the necessity of external water for the development of the spores into the typical land plant was completely eliminated by the development of these spores on the plant itself. The result was the seed, in which the old separate prothallial stage was completely bound up. The impetus toward such a change had doubtless been present somewhere on earth throughout its entire history in the growing aridity of various regions. When some plants had evolved to a state in which they could get rid entirely of the necessity of external water for fertilization, they were naturally urged by these physical conditions to do so. The result was the occupation of the drier lands. Since this new type of plant had both fernlike vegetation and true seeds, it is aptly called a seed-fern — technically Pteridospermæ (Greek *pteris*, a fern, and *sperma*, seed) or Cycadofilicales (from *Cycas*, and *filicales*, ferns) — because in some respects it appears to be transitional between the ferns and the next higher groups of seed plants, the cycads and cycadeoids.

When comparing such a typical seed-fern as Lyginodendron of the Pennsylvanian with living plants we see that it had the habit of a small tree-fern and that the structure of the stem when young was remarkably like that of the royal fern (*Osmunda regalis*), while in its later growth there was a considerable resemblance to the structure of a cycad stem. The seeds resemble those of the modern cycads and the Ginkgo in the possession of a hollow chamber at the apex of the ovule (egg) to catch the pollen. In the water secreted within this chamber the male cells developed by the pollen grains swim to the female cell within the ovule. The seeds and pollen sacs were borne on portions of the ordinary vegetative frond that were little altered, but from which the ordinary leaflets were absent; that is, there were no flowers or cones. The rounded seed was about the size of a hazelnut, though varying from a quarter of an inch to two inches in diameter. It was much like that of the cycads, with a thick, fleshy outer coat over a stone inclosing the fertilized ovule. In none of the seeds observed was there an embryo; this, then, developed during the germination of the seed after its rest period (D. H. Scott).

Seed-fern types were very abundant during the upper Paleozoic, especially throughout the Pennsylvanian. Of the important genera, Neuropteris included tree-like forms with a trunk up to 2 feet in diameter, terminating above in large fronds, while Pecopteris, with Neuropteris-like fronds, and Aneimites, with fronds as in the living maidenhair fern, had flattened seeds, approaching the cone-bearing Cordaites in this respect. Lyginodendron had some species that resembled small tree-ferns, while others probably climbed to some extent, since the stem and leaves were covered with spines.

The earliest known terrestrial forests, the two Gilboa forests of upper Devonian age in Schoharie County of eastern New York, consist of seed-ferns of the genus Eospermatopteris. These were swamp-dwelling trees reaching a height of from 30 to 40 feet. The bulbous base of the stump varied in diameter up to 11 feet (Fig. 137, *i*). To this bowl-like base were attached numerous small roots that reached a diameter of an inch or more and a length of over 6 feet. The seed was oval and inclosed in an outer husk (W. Goldring).

Cordaitales—the large-leaved evergreen trees. Evolving from primitive seed-ferns, or probably along with the seed-ferns from the older fern stock, developed the now extinct Cordaite order of plants. Apparently the land plants had become sufficiently advanced to be stimulated by any new environment of greatly increased land area, so that they entirely lost the outward signs of their fern ancestry. The members of this order are allied, more or less closely, to the seed-ferns, cycadeoids, cycads, ginkgoes, and conifers. The advanced stem structure is connected with the simpler one of the seed-ferns by many intermediate forms. The ovule and seed are essentially the same as those of the seed-ferns and the living cycads, while the leaves have the same internal structure as those of some living cycads. The nearest living relative of Cordaites, the Ginkgo, or maidenhair tree, called by some "a living Cordaite" and by Darwin "a living fossil," has similar reproductive organs. The cycadeoids, cycads, seed-ferns, and cordaitean forms, either ancient themselves or of an ancient type, have pithy stems, while the ginkgoes, conifers, and perhaps some later cordaitean species have more woody stems, showing a differential pith reduction.

Cordaites was a tall, slender tree, reaching a height of 120 feet and a trunk diameter of 3 feet. The stem, which had a wide pith center reaching a diameter of 5 inches, grew by external additions of wood, while the bark covering was thick and complex, as in so many other Paleozoic trees. These tall evergreen trees had the foliage confined to the upper quarter, where it formed a dense crown of branches with numerous grasslike leaves. Some leaves had a breadth and length of half an inch by 20 inches, and others of half a foot by 6 feet. The reproductive organs, both male and female, were catkins, and so were intermediate between the primitive reproductive fronds of the seed-ferns and the specialized cones of the conifers. The pollen sacs, as well as the ovules, were raised upon short stalks. The plumlike, flattened seed had a fleshy outer coat covering the stone which inclosed the fertilized ovule.

The cordaitean order rivaled the conifers of later periods. The name is from its principal genus Cordaites, named in honor of A. J. Corda, an early student of fossil plants.

This type of plant, originating before the upper Devonian, became very abundant by the Pennsylvanian, and at that time many of its representatives were huge trees. It could not, however, compete with the later higher gymnosperms, owing especially to its primitive reproductive organs and foliage, and hence gradually died out in the early Mesozoic. Yet before it disappeared from the earth it had left offspring or relatives destined to carry still higher, in the Coniferæ, the type of evolution it had so well begun.

Coniferales, the conifers,— the needle-leaved, usually long-trunked evergreen trees. Under the impetus, apparently, of the changing environment initiated by the glacial period of the early Permian, some of the more plastic woody-stemmed forms of the Cordaitales gradually evolved into the Coniferales. The tube cell of the pollen grain elongated, thus getting rid of the pollen chamber at the tip of the ovule for the secretion of water. The earliest known form of this new type is the Permian genus Walchia, which apparently belongs to the

Araucarian conifers. The Araucarians at one time spread over the Northern Hemisphere but are now mainly restricted to the Southern, the Brazil pine forming the greatest single forest, although the best-known form is the Norfolk Island pine of the Australian region. The latter has whorls of horizontal branches closely set with awl-shaped leaves. In its native habitat it is a tree upward of 200 feet in height, with a top, as Darwin said, "out of all proportion small to its trunk," massive and stately as a granite column. As a popular house plant it seldom reaches a height of more than two or three feet.

The Araucarian conifers are said by some to be the most primitive of living Coniferales; and they certainly appear closely related to the Paleozoic Cordaitales in many ways, especially in the structure of the wood. For example, the resin tracheids, in the xylem, are not differentiated in structure from the surrounding tracheids, nor specialized as secretory reservoirs. Among the living gymnosperms this primitive condition is almost confined to Araucaria, but the Cordaitales possess this as an essential character. Gradually the resin tracheids became specialized, first into resin cysts, as in Sequoia and Abies; later these cysts became merged into continuous canals, typical of the highest conifers, Picea and Pinus (Penhallow). The foliage also retains a very ancient cast. Nevertheless an imposing array of botanical authorities view Araucaria as merely the most specialized conifer.

The conifers are also represented in the Permian by Voltzia, a probable ancestral sequoia, another primitive conifer. Such small, probably sand-barren forms as Walchia and Voltzia continued throughout the Triassic. They were accompanied in the upper Triassic by huge trees belonging to the Araucarian family; an example is the genus Araucarioxylon, with trunks over a hundred feet long, which is so abundant in the Petrified Forest at Adamana, Arizona (Fig. 87). Under the impetus of the colder climate of the uppermost Triassic and lowest Jurassic the existing conifers radiated into many new types; hence by the middle and upper Jurassic we find preserved ancestral forms of not only the sequoia but of the yew, cypress, arbor vitæ, and even pine.

The conifers have gradually declined during the upper Mesozoic and Cenozoic until but a remnant, less than three hundred species, survive today. This decline may largely be due to unsuccessful competition with the larger-leaved angiosperms. While the resin poured forth by an injured conifer, especially by one of the higher forms, effectually heals a wound, and thus gives these trees comparative freedom from insect and fungus attacks, they succumb to the lack of sunshine brought about by the spreading, dense-leaved dicotyledons.

Ginkgoales, the maidenhair trees, — lobe-leaved, deciduous trees with much-branched trunk. Apparently the stock and environment which gave rise to the Coniferales evolved likewise this type of plant. The ginkgoes are the nearest living representatives of the Cordaitales; they are especially similar in their reproductive organs, including the motile sperms (the last traces of their amphibious origin) and their plumlike seeds. Being thus nearer to the ancestral form than are the conifers, the ginkgoes are often spoken of as the connecting link between conifers and Cordaites.

This type of plant, which appeared first during the Permian in such ancestral forms as Saportea and Baiera, is characterized by small lobate leaves, like the leaflets (though larger) of the maidenhair fern Adiantum. It apparently reached its maximum in the Jurassic. The living genus Ginkgo is known from the Triassic to the present, being the most ancient of all hardwood trees. It would probably have become extinct before now if it had not been regarded as sacred in China and Japan, where it is grown in the gardens of the Buddhist temples. It is now widely cultivated throughout the temperate zones.

Cycadeoids, or Hemicycadales, — the presumable ancestors of flowering plants. Evolving from some seed-fern or seed-fern-like types under the impetus, probably, of the changed environment initiated by the Permian glacial period, appeared a type intermediate between the living cycads and the angiosperms. This type, named Cycadeoidea, because it has the external form of the living Cycas, came in with the Permian and had a very great development during the early and middle Mesozoic (Fig. 137, *j*). The cycadeoids, the dominant portion of the early Mesozoic flora, were world-wide in their distribution, being known from arctic Greenland and Siberia through the tropics to Louis Philippe Land of the Antarctic. Wieland has estimated that on the average two out of every five of the land plants of the Mesozoic were of the cycad type. The majority of species lived in moist regions, but some scrub forms apparently indicate a desert habitat (Wieland). In North America they have been preserved in abundance in Maryland, South Dakota, Wyoming, and Mexico. In the Black Hills of South Dakota a thousand silicified specimens, referred to a dozen or more species, have been found.

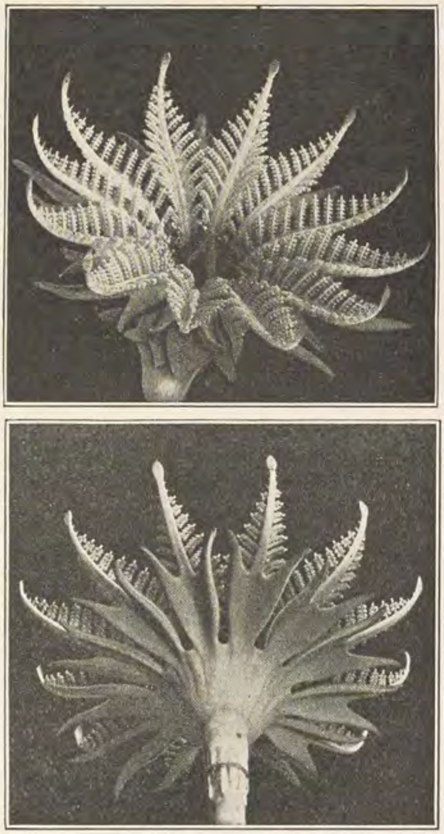


Fig. 119. Restoration of a cycadeoid flower

Two views of a glass model of the flower of a Mesozoic cycadeoid. Note the central seed-bearing cone surrounded by stamens, each of which has the form of a pinnate fern frond. Outside the stamens (making up most of the flower) are bracts corresponding in position to petals and sepals. In the view below the bracts have been removed. (From the Field Museum, Chicago, model by Dahlgren; based upon dissections by Wieland)

The cycadeoids were much like the shorter-stemmed cycads of today in stem and leaf structure. The stem was similarly clothed with the old leaf bases. Their origin from the seed-ferns is suggested in the retention of the frondlike stamens. The pollen sacs are divided into numerous compartments and are structurally almost identical with those of the living Marattia family of ferns. They resemble the flowers of the angiosperms, especially the tulip tree, in possessing a central seed cone surrounded by basally attached stamens and an outer series of bracts corresponding to sepals and possibly also to petals (Fig. 119). These large, beautiful flowers were probably visited by the lower insects then living, for even the cones of the living cycads are frequented by insects which may thus serve as pollen carriers. Whether these flowers were colored other than green or brownish red is not known; but since the fruit of living cycads is red, this primitive color may have characterized the cycadeoid flowers. The seeds were much like those of living pines, while the embryo, with its two cotyledons, indicates an ancestral relationship to the dicotyledon division of the angiosperms. Since the ovules were apparently exposed and hence fertilized directly by the pollen grains, the cycadeoids are classed as gymnosperms and not as angiosperms. Instead of having the flowers borne a few at a time from the top of the stem, as are the cones in the living cycads, they were borne laterally between the leaf bases in great numbers. In a single specimen of *Cycadeoidea dacotensis* from the Lower Cretaceous there were sixty-one flower buds. The stem had a ring of wood and bast surrounding a wide pith center.

The cycadeoids died out before the close of the Mesozoic. The group was specially fitted to play the dominant rôle in plant life during the earlier Mesozoic but could not survive the competition with its offspring, or nearest competitors, the angiosperms, during the later Mesozoic.

Cycadales, the cycads. This type, evolving either directly from the cycadeoids or from the seed-ferns, had no great development either during the Mesozoic or later. Never a dominant class, the incoming of the angiosperm type affected it but little, probably because it did not come into direct competition with it, and hence it survives to the present. The living cycads are mostly tropical plants. In external appearance they are intermediate between the tree-fern and the palm. The best-known living form is Cycas, fossil forms of which are known from the lower Jurassic to the present. *Cycas revoluta* from Japan is a common conservatory plant.

The flowering plants — the angiosperms. The great step giving rise to the angiosperms was the inbending of the edges of the megasporophyll until they met, thus entirely inclosing the ovule, whence the name *angiosperm* (Greek *angeion,* a vessel, and *sperma,* a seed). As the megasporophyll became a closed vessel its outer top (the stigma) developed a nutritive sticky surface; that is, there occurred a transfer of the pollen-collecting surface from the ovule to the protective leaf. This closure was naturally accompanied by a longer growth of the tube cell of the pollen grain (Fig. 120). In the cycadeoids, unlike the living gymnosperms, the embryo filled almost the whole of the interior of the seed, and there were present two cotyledons, as in the dicotyledons.

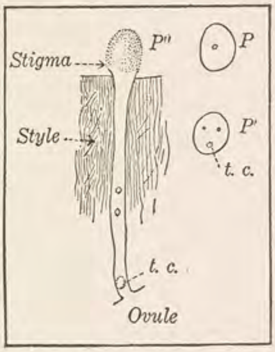


Fig. 120. Gametophyte stage of the elm, enlarged

The gametophyte stage, corresponding to the entire liverwort plant, is passed entirely within the pollen grain and ovule of the mature angiosperm plant, the sporophyte. The prothallus of the pollen grain consists of three cells as shown; that of the ovule consists of several cells (not shown in the figure). The cell resulting from the union of a cell from the pollen grain and of one from the ovule grows rapidly into the seed, the beginning of the sporophyte stage. *P*, pollen grain with its single included nucleus; *P'*, the same at a later stage with three nuclei; *P''*, the same lodged upon the sticky stigma, with the tube cell already within the ovule; *t.c.*, tube cell. (See Fig. 116.) (Courtesy of the Macmillan Company)

The dicotyledons. Sometime during the middle Mesozoic, probably under the impetus of the earth revolutions of the upper Jurassic, arose the dicotyledon class of the angiosperms. Apparently this evolution has been largely aided by adaptation to contemporary insect life. Primitive species of beetles, flies, ants, bees, wasps, and butterflies were present during the upper Jurassic, and each of these families has continued to evolve new species especially adapted to the more and more efficient crossing of the flowers. This naturally resulted in stronger and more variable flowering plants.

The monocotyledons. Another offshoot from near the primitive ancestral dicotyledons evolved into the monocotyledons, apparently because it became adapted to very moist conditions. The majority of the 25,000 species of living monocotyledons are adapted either to very moist conditions or to the derivative of these — underground life — as seen in underground stems and bulbs. Such a comparatively uniform environment would tend to produce uniformity and simplicity of structure, with general loss of secondary growth. The leaves became simple, smooth, elongate, with margins usually entire. The stem is composed largely of pith, through which may extend many vascular bundles, derived entirely from the leaves; there is reduction usually to total absence of the cambium, and hence the stem can increase but slightly in diameter, thus giving the characteristic columnar appearance seen in the stems of grasses, bamboos, and palms. Such families as the grasses give further indication of aquatic origin in their underground stems, like the similarly derived underground stems of the club mosses. Much later some forms, such as the silica-impregnated grasses, became adapted to dry lands. Though grasses, in coarse species, had been known from the Cretaceous and in some forms from the earlier Tertiary, there is no evidence that they had evolved the prominent underground stems and drought-resisting qualities essential to a plains habitat before the early Miocene; for all ungulates before the Miocene were browsers with comparatively short-crowned teeth, which dry siliceous grasses would quickly have worn to the gums.

The single cotyledon of the monocotyledons was apparently derived from the two of the cycadeoids through arrest in the development of one of them, that is, through the continuation of one growing point instead of two. Such an origin is apparently corroborated by the presence, in the embryo of most grasses, of an accessory organ, the epiblast, which is interpreted as a vestigial cotyledon (Coulter).

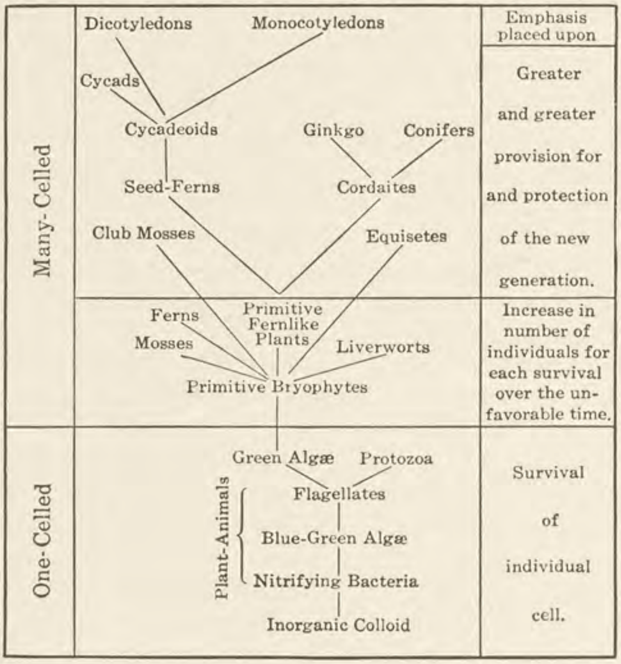
The dicotyledons and monocotyledons, first known to us from the Lower Cretaceous of North America and Europe in such forms as the sassafras, poplar, magnolia, and sedges, spread over the earth during the Upper Cretaceous, and they have continued this distribution to the present. Fossil palms as far back as early Upper Cretaceous are recorded in a fossil coconut, with the familiar three holes in the shell.

SUMMARY OF EVOLUTION OF LAND PLANTS

Among the lines of variation to be noted in the evolution of the plants is their increasing independence of external water (except that derived through the roots), the growing dominance of the land (or sporophyte) generation over the water (or gametophyte) generation in size, an ever-greater protection of the new generation by the parent plant, and the replacement of a cellular structure with a fibrovascular one with its greater supporting possibilities. The earliest plants were tied to the water; water fed them, held them up, kept them from drying up. Water was necessary for reproduction. The first step landward was taken when some of the plants living in habitats where the water at times dried up formed spores that carried the species over to the next return of the water. This stage persists today in some of the algæ. Later some plants developed root hairs and a more resistant tissue which enabled the entire plant to survive as long as the habitat remained shady and moist. This is typified in a very general way by the liverworts. Still later some of these plants evolved true roots, and, in addition, vascular woody fibers and hence stems and leaves. The necessity, however, of external water for reproduction prevented these plants (the ferns, horsetails, and club mosses) from becoming true land plants. Later from such amphibious types arose individuals which nourished the sexual stage (the water generation) within themselves, instead of leaving it a self-supporting plant, and thus did away with the necessity of external water during reproduction. Thus seed plants, the only true land plants, finally came into existence.

Judging from fossil remains and the embryology of living forms, the evolution was in general along the lines indicated in Fig. 116 and Tables XIV, XV,—from one-celled forms through colonial to many-celled forms, and from a water habitat through an amphibious to a land habitat. With the plant continuously submerged, as the earliest forms must have been, reproduction was at first by simple subdivision. Later some of the individual cells surrounded themselves with hard protecting coats (then called spores) to carry them over periods unfavorable to growth. Later still the union of active spores (called gametes) initiated sex, producing stronger and more variable individuals. Gradually, in some forms, the cells arising from the subdivision of a cell remained temporarily or permanently in contact, but each cell retained the ability to perform all essential functions; these are colonial species. Later, as some cells assumed a protective function, others a reproductive, etc., the various cells must remain in contact for continued existence and reproduction, and the many-celled individual came into existence. These many-celled species continued to evolve gradually from an entirely submerged state (seen in the various seaweeds of today) to a land (a dry-air) habitat. As a preliminary step the sex cells, the gametes, which had heretofore united by chance in the water, were united upon the plant

TABLE XV. THE EVOLUTION OF PLANTS



and there nourished. This is probably the most important of all variations that occur in the evolution of plants. It is comparable in a way with the retention and nourishment of the fertilized egg within the ovary in animals, producing thereby the great class of mammals. At first the plant producing the sex cells nourished the fertilized individual (sporophyte) until it had developed spores, as in the higher algæ and bryophytes. Later, as in the ferns, the fertilized spore was nourished by the plant producing the sex cells, the gametophyte, for a short time only, after which it became self-supporting by the development of roots and leaves. This was necessarily accompanied by development of vascular fibers, that is, by having the cells arranged end to end. Thus in the higher algæ, the bryophytes, and the pteridophytes there came about an alternation of a sporophyte generation (the plant producing the spores) and a gametophyte generation (the plant producing the sex cells — the gametes). The next step in the development of land plants, as in animals, was the dropping out of the amphibious stage. A necessary preliminary step in this direction in plants was the pushing back of the sex difference to the spores. The spores, instead of being all of a uniform size, as in the living bryophytes, ferns, horsetails, and many club mosses, are of two sizes. In some species of the Paleozoic Calamites the female spores (the megaspores) have a diameter about three times that of the male spores (the microspores).

In the higher plants today the microspores, known as pollen, are often 1/100,000 the size of the large female megaspores, known as ovules. The resultant male prothallus develops only male gametes, and the female only female gametes. The union of these produces the sporophyte generation. The next step is the obliteration of the early water stage through the nourishment of the prothallus upon the parent plant. In the early land plants, in order that the spores may develop into the large sporophyte, external water must be present at two different times — once for the germination of the spore and its growth into the prothallus, and again for the swimming of the male gametes to the female. Hence, any land plants that might evolve in the direction of getting rid of the early water stage would have a better chance of having their offspring survive, and so of perpetuating their kind, under the moisture variations then present. This is seen in the living club moss Selaginella and in the tree club mosses of the Paleozoic. Here the spores are of different sizes and are borne upon different parts of the cone. Each is nourished upon the cone through a separate, nongreen prothallus stage, after which it is usually shed. After falling to the ground, if water is present the male cells developed in the male prothallus swim to the archegonium of any female prothallus, attracted by its secretion of malic acid, as in the fern. Thus fertilization results and the consequent growth of the young sporophyte takes place.

The next great step in advance, the abolishing of the necessity of external water for fertilization, resulted in the seed. This was brought about by the retention of both female and male prothallus by the cone. The prothalli were so greatly reduced in size that they developed within the spores. A protecting coat was developed about the greatly enlarged female spore, at the tip of which some water was secreted. After the male spores, usually microscopic in size, were carried by the wind into the water, the male gamete escaped and, swimming to the female gamete, caused fertilization. After this the female spore and its protecting coat, called the seed, was shed. Since this protecting coat is open at the top for the reception of pollen (male spores) plants bearing this type of seed are called gymnosperms (Greek *gymnos*, naked, and *sperma*, a seed). In such Paleozoic gymnosperms as the seed-ferns the entire growth into the sporophyte generation took place after shedding; that is, there is no embryo in the seed. Later, in higher gymnosperms, this early growth of the sporophyte takes place on the parent plant, after which it is shed (for example, in the pines). In some of the higher gymnosperms the water at the tip of the ovule is replaced by a mucilaginous secretion which holds the pollen grain until it extends a pollen tube down which the male gamete is carried by the ordinary current of protoplasm present in every cell. It was probably the widespread desert conditions of the upper Paleozoic that were responsible for the anticipation within the seed of a part of the growth of the herb or tree. Deserts, with their short growing season, would place a premium on those plants which would develop the early stages (that is, the embryo) of the new sporophyte within the seed while still on the parent plant; for such seeds would need a very much shorter wet and warm period than those which must develop the entire plant from the time of fertilization, as in the seed-ferns. Thus the embryo, made up of the very young stem, roots, and leaves, enables the seed to take advantage of even a very brief period of moisture.

The next step was the enrolling of the megasporophyll. (This corresponds to the scale of the cone of the gymnosperms, at whose base is the naked female spore (the ovule), which when fertilized becomes the seed.) Since the ovule is thus protected, these plants are called angiosperms. In other words, the megasporophyll is a leaf rolled into a closed pod, as a pea or bean pod. Hence, since the ovule is inclosed, the tip of the leaf must have a sensitive surface (stigma) to hold the pollen grains. Since fertilization is brought about not only by wind but also by insects, there developed odor, nectar, and bright flowers to attract them.

The majority of the oldest known flowering plants, those from the Lower Cretaceous, belonged to the more primitive orders and mostly to the more primitive of the two existing series of dicotyledonous flowering plants, the Choripetalæ. Apparently most, if not all, of these had greenish-yellow, greenish-white, or white flowers, if we may judge from their nearest living relatives. For example, of these persistent genera from the Lower Cretaceous, the poplar, sassafras, elm, and oak have today greenish-yellow flowers; aralia, greenish-white; and magnolia, white. Such highly modified and varicolored parts of flowers as hoods and wings are, according to fossil remains, apparently of late Cenozoic development, and they occur only on the more advanced of living species. Thus paleontology and the development of highly modified parts of the flower agree in indicating that the earliest angiosperm flowers on earth, those of the upper Mesozoic, were green, yellow, or white, and of a uniform color. The higher colors, the blues and purple, together with the veinings and mottlings, came in gradually during the Cenozoic.

TABLE XVI. TABULAR VIEW OF THE PLANT KINGDOM

Phyla and classes are arranged from the simple and more primitive, below, to the higher and more complex, above

PHYLUM	CLASS		KNOWN RANGE	COMMON NAME OR LIVING EXAMPLE
IV. SPERMATOPHYTA (seed plants)	Angiospermæ	Dicotyledones	Lower Cretaceous to present	Oaks
		Monocotyledones	Lower Cretaceous to present	Grasses
	Gymnospermæ	Gnetales	(Fossil record scant)	Ephedra
		Coniferales	Permian to present	Pines
		Ginkgoales	Permian to present	Ginkgo
		Cycadales	Triassic to present	Cycads
		Cycadeoidea	Permian to Cretaceous	Cycadeoids
		Cordaitales	Devonian to Permian	Cordaites
		Cycadofilicales	Devonian to Jurassic	Neuropteris
III. PTERIDOPHYTA (fern plants)		Lycopodiales	Devonian to present	Club mosses
		Sphenophyllales	Devonian to Permian	Sphenophyllum
		Equisitales	Devonian to present	Horsetails
		Filicales	Devonian to present	Ferns
II. BRYOPHYTA (moss plants)		Musci	Mississippian (?) to present	Mosses
		Hepaticæ	Silurian (?) to present	Liverworts
I. THALLOPHYTA (thallus plants)		Fungi	Silurian to present	Fungi
		Diatomeæ	Jurassic to present	Diatoms
		Algæ	Pre-Cambrian to present	Seaweeds
		Myxomycetæ	(Fossil record lacking)	Slime molds
		Schizophyta		
		Blue-green algæ	Archeozoic to present	Blue-green algæ
		Bacteria	Proterozoic to present	Bacteria

TOPICAL REVIEW

- Introduction
- The incoming of life — the step from an inorganic colloid to protoplasm
  - The assembling of the various elements to form protoplasm
  - The incoming of the life energy
  - Sources of energy
- Plant-animals — the earliest earth life
  - Oxidation of inorganic substances. Nitrifying bacteria
  - Sun's rays acting through phycocyanin. Blue-green algæ
  - Summary of origin of living forms and geological evidence
  - Sun's rays acting through chlorophyll. Flagellates
- True plants, aquatic and amphibious
  - One-celled green algæ
  - Many-celled green algæ
  - The first great step upon land — primitive bryophytes
    - Geological evidences as to the great antiquity of the bryophytes
  - The second great step in the development of a land flora — the ferns
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    - Fossil ferns
  - Equisetales, the horsetails
    - The Paleozoic tree horsetails (Calamites)
  - Lycopodiales, the club mosses
  - Summary of evolution of the pteridophytes
- True land plants
  - The earliest true land plants — the Cycadofilicales, or the seed-bearing ferns
  - Cordaitales — the large-leaved evergreen trees
  - Coniferales, the conifers, — the needle-leaved, usually long-trunked evergreen trees
  - Ginkgoales, the maidenhair trees, — lobe-leaved, deciduous trees with much-branched trunk
  - Cycadeoids, or Hemicycadales, — the presumable ancestors of flowering plants
  - Cycadales, the cycads
  - The flowering plants — the angiosperms
    - The dicotyledons
    - The monocotyledons
- Summary of evolution of land plants

CHAPTER XIX

A HISTORY OF THE ANIMAL LIFE OF THE EARTH

Animals constitute that branch of life in which freedom of movement is emphasized. Increasing independence of environment was attained, largely through the instrumentality of an increasingly complex and sensitive nervous system. The partial and broken record of their evolution which is preserved in the fossils of the rocks of the earth must be supplemented by the comparative anatomy and embryology of the animals of today. In such manner we may gain some knowledge of the descents and relationships of animals both past and present.

PROTOZOA, COMPRISING UNICELLULAR ANIMALS

It has been seen that the earliest beginnings of life on the earth were probably embodied in plant-animal forms, the higher of which were similar to the modern flagellate Euglena. From the more freely moving of some such forms arose the animal line; from the more static, the plants (Fig. 135). Thus from the flagellates (typified by Euglena) evolved the Protozoa (p. 306). Foodstuff developed by the plant-animals and plants was lying about ready for the taking by any organism that developed the necessary ability to move sufficiently. The flagellates could move slightly and secure some of this organized foodstuff, though they must still manufacture some of their food through the action of the sun's rays. The Protozoa discarded the inorganic source of food, depending entirely upon organized foodstuff.

THE DEVELOPMENT OF MULTICELLULAR ANIMALS

Larger plants or animals have fewer enemies than smaller ones. The minute protozoöns are eaten by all larger animals and are smothered by mud and sand. Some of the minute one-celled organisms united into colonies, as does the protozoön Microgromia today. In this genus any member of the colony may break away and start an independent life; at times the entire colony disintegrates and each individual becomes a separate protozoön. It is conceived that from such colonies arose the many-celled animal, a development that would naturally result as subdivision of labor entered and the individual cells could not break away, since each was dependent for its well-being upon its close connection with other cells.

The earlier many-celled animals, because of their low stage of evolution, found it easier to fix themselves, as did plants under similar conditions, to some solid object to keep from being drifted on shore. They then necessarily depended upon the currents, which they had overcome, to bring the helpless one-celled and other microscopic organisms to them as food. Being now safe from the ordinary drifting sediment and the force of the currents, as well as assured of a more or less regular supply of food, it was natural that, like plants under very similar conditions, they should further support and protect their bodies by means of some hardened material. In the plants this support was woody fiber (cellulose), but among animals, probably because of an entirely different food supply, cellulose is rarely secreted.

SPONGES

In the sponges, the simplest of existing multicellular animals, the supporting material is of silica, of lime, or of spongin, the last being well known as the material of the ordinary bath sponge. In the sponges is seen a very primitive condition of subdivision of labor. Some cells develop the supporting material while other cells perform digestion. This phylum probably arose directly from the plant-animal group of the flagellates, the Choanoflagellata.

The sponges are usually attached by a broad base. When animals became attached by a narrow base, gravity would naturally force them to become symmetrical about the point of attachment, just as plants are. Hence such animals tend to radiate from a center. This is especially true of the representatives of the two typically attached phyla, the cœlenterates and the echinoderms.

CŒLENTERATA

In another direction some early many-celled animals developed the outer cells into a locomotor as well as a protective surface, the inner cells being digestive. Activity is almost wholly confined to the movement of the arms (tentacles) developed around one end of the barrel-shaped body. On the approach of danger these food-procuring tentacles roll up, thus shortening the body. Accompanying this subdivision of labor was the growth of short nerves as a means of communication between the various groups of cells. Since in the Protozoa the entire animal is made up of the sensitive protoplasm and is very minute, no nerve threads have been evolved, nor are they needed. In the cœlenterates some ordinary body cells have elongated and become more sensitive; these are the primitive beginnings of nerves.

The earliest fossil cœlenterates appear in the Cambrian; but since fossil annelid worms are known from the upper Proterozoic, and since these worms today pass through a cœlenterate stage during their extreme youth, this phylum would seem to have had representatives early in the Proterozoic.

During the Paleozoic, fossils of both main classes — hydrozoöns (Fig. 81) and corals (Fig. 84) — are found, but they are primitive representatives of the classes. The corals gradually change from single individuals to colonial forms, for colonies forming broad and high masses rise above the drifting muds and thus tend to be killed off less frequently than simple corals.

WORMS

In some of the primitive cœlenterates the tendency to move forward was sufficiently great to overcome the downward pull toward fixity, and gradually the various classes of worms arose.

In some of these forms active movement in one direction led to the development of a head end to the body, with consequent right and left sides. Since in the lower classes of animals eating is the most important activity, the earliest grouping of nerves naturally took place around the base of the mouth, that is, the throat or esophagus. This very important grouping of nerves around the esophagus is called the circumesophageal nerve ring and is characteristic of all animals below the vertebrates and above the cœlenterates. Besides the circumesophageal nerve ring the annelid worms possess a nerve ganglion, or primitive brain, in the head and a ventral coördinating nerve cord with ganglia extending the length of the body.

ECHINODERMATA

In the echinoderms, all of which are entirely marine, protection took the form of small plates of carbonate of lime embedded in the outer cells of the body, the skin. As the animal grew in size these plates became larger, and so continued to protect the essential organs within.

The echinoderms apparently arose from free-moving forms, like worms, through the development of a protecting skeleton of small calcareous plates within the skin and the evolution of five radial grooves (ambulacra) which are pierced by cilia or by tubelike feet, according as their function is food-getting or locomotor. In forms, such as the cystoids, blastoids (Fig. 140, *b*), and crinoids, which have anchored themselves as an added protection the grooves are lined with cilia which urge the microscopic food particles, brought thither by chance, to the mouth. In the individuals of such animals as the starfish (Fig. 121), brittle stars, sea urchins (Fig. 121), and sea cucumbers, which go in search of food, the grooves are pierced with sucker-tipped tube feet; these eat such large food masses as oysters.

The five ambulacra give to all echinoderms a definitely fivefold division of body, such as five arms or five grooves. These may increase in number by branching, but they generally remain a multiple of five.

The earliest fossil echinoderms, the cystoids, are found in the Cambrian. The fixed echinoderms, better protected but less energetic, attained their maximum in the Paleozoic, two of the classes, the cystoids and blastoids, not surviving the close of that era. The freely moving forms have held their own to the present.

MOLLUSCOIDEA

The molluscoids (Fig. 122) probably evolved from some lower group of worms. Being of a low nervous organization, with a consequently primitive type of body structure, the majority of these ocean-dwelling forms anchored themselves to some more or less stable object. Being fixed, the molluscoids had to depend upon the food that the water currents brought them. Since this food was mostly microscopic, grooves leading to the mouth were developed, as happened under similar conditions in the fixed echinoderms. Any food particle touching these grooves would be urged downward to the mouth by the short, vibrant hairs lining them. Unlike the echinoderms, however, molluscoids secreted an external skeleton. The individuals of one class of the molluscoids, the Bryozoa (moss animals), are

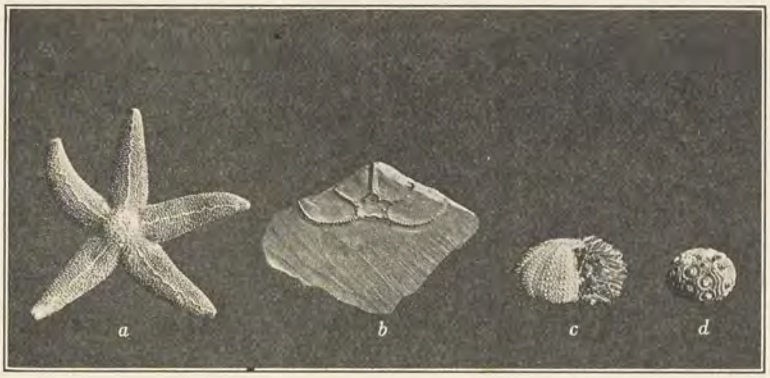


Fig. 121. Freely moving echinoderms

a, the modern starfish Asterias, from Long Island Sound; *b*, a fossil starfish from the Devonian of Germany; *c*, the modern sea urchin Strongylocentrotus, from the Maine coast (spines removed from part of the shell); *d*, the fossil sea urchin Cidaris, from the Jurassic of England. (Scale: Cidaris (*d*) is one inch high) small, often growing in mosslike colonies. They surround the bases of their bodies with a secretion of lime, or chitin. The individuals of the other class, the Brachiopoda, lead separate lives and secrete for protection two valves of lime carbonate, as do the common clams of the phylum Mollusca.

The earliest fossils of both these classes are known from the Cambrian, but their development in this period indicates that they must have evolved during the preceding Proterozoic. From the Cambrian onward they rapidly radiate into thousands of species and numberless individuals. Many rock masses hundreds of feet thick are made up entirely of bryozoans and brachiopods. They attained their maximum in species and number in the Paleozoic and have decreased to the present.

Fig. 122. Fossil representatives of the marine Molluscoidea

At the left, a rock made up entirely of shells, brachiopods, *Dalmanella testudinaria*, and a few twiglike bryozoans, from the Ordovician of Ohio; at the right, the brachiopod Spirifer, from New York; in the center, a bryozoan from the Ordovician of Indiana. (Scale: the rock mass at the left is three inches high)

MOLLUSCA

In one or more lines of annelid worms the tendency toward change was sufficient to lead gradually to the development of a new and higher phylum of animals. In these the development of much better blood-circulatory and respiratory systems hastened the repair of waste and brought in more oxygen, thus leading to an increase in bodily activity.

The mollusks are a distinctly higher group of animals than the protozoöns, sponges, cœlenterates, echinoderms, and molluscoids; they have a nearer approach to man in their many body organs. Thus the mollusks have organs for getting food and reducing it to small particles, a stomach to digest it and intestines from which it may be absorbed, blood vessels to carry it to all parts of the body and a heart to force it there more perfectly. As blood gives food to all parts of the body, so it also gathers up the broken-down cells. To take this waste matter from the blood the kidneys were developed. In the performance of the bodily functions, heat is necessary; for the development of heat, oxygen is an essential in addition to food. By means of outpocketings of some part of the body, oxygen must be procured from air diffused in the water. With the oxygen on the outside of the thin membrane forming the outpocketing (gills), and with blood on the inside, an osmotic interchange of the oxygen for the waste gases easily takes place.

In this phylum are included the pelecypods (clams etc.), gastropods (snails etc.), and cephalopods (squids and nautilus). Though many of the *pelecypods*, as, for example, the oyster, became degenerate through ceasing to struggle against the waves by cementing their shells to stones on the sea bottom, many, like the scallop (Pecten), move freely and rapidly from place to place by the rapid opening and closing of their bivalve shell. In the next higher class, the *gastropods*, freedom of movement is maintained; but since the organ developed is a creeping foot, movement is slow though well directed. In the highest class, the *cephalopods*, still another mode of progression was evolved. The edges of the fleshy fold, the mantle, surrounding the body became united to form a water-squirting funnel, which, used like the oar of a boat, forced the animal backward. These organisms won the supremacy of the seas early in the Paleozoic time, but in the later Paleozoic they had to compete with the more lately evolved fishes. Throughout the Mesozoic, notwithstanding the fierce rivalry of the marine reptiles and fish, both the forms with external shells and the unprotected Mesozoic squids, the belemnites, reached their climax. In places the seas literally swarmed with them (Fig. 124, *f*).

The most primitive class, the *chitons* (Fig. 123, *a*), retain the transversely segmented character of the annelid worms. The earliest fossils of these, so far known, are from the Ordovician.

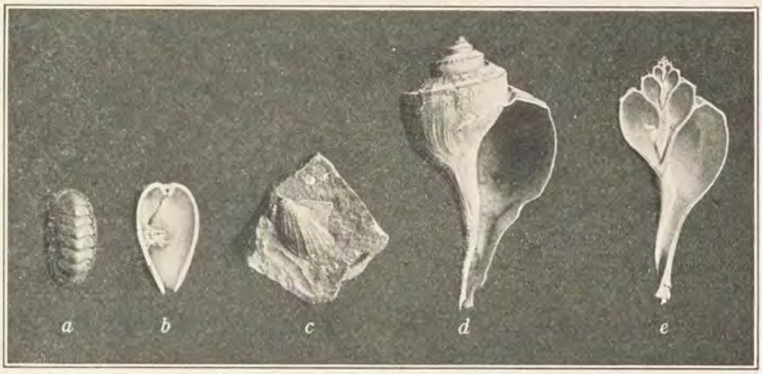


Fig. 123. Marine representatives of the three lower classes of mollusks

a, surface view of the chiton. This representative of the most primitive class of mollusks still retains superficial affinities with the worms. *b*, the sectioned shell of a pelecypod, the quahog (Venus), showing the anterior muscle. *c*, the pelecypod *Pterinea flabella*, abundant in the Devonian seas of New York and elsewhere. *d*, *e*, the shell of the gastropod *Busycon canaliculatus*, entire and sectioned. The soft parts of the animal occupied the entire shell. (Scale: the chiton (*a*) is two inches long)

The pelecypods (Fig. 123, *b*, *c*) first appear with definite fossil remains in the Ordovician. Throughout the lower Paleozoic they remain small and thin-shelled, with two muscles for closing the shell. With the upper Paleozoic the shells became heavier, with a broad hinge area and in many genera with a survival of only one muscle. The gastropods (Fig. 123, *d*, *e*) are represented in the Cambrian mostly by thin, straight shells; the Ordovician saw a rapid development in size, kinds, and number. Gastropods, as well as the higher types of pelecypods, have continued to increase to the present. The cephalopods are also first known from the Cambrian. Of the more primitive subclass

Tetrabranchiata (with four gills), the order Nautiloidea (Fig. 124, *a*, *b*), which is characterized by straight or curved sutures, is dominantly Paleozoic, while the order Ammonoidea (Fig. 124, *c*, *d*, *e*), which is characterized by complicated, fernlike sutures, is dominantly Mesozoic. The more advanced subclass Dibranchiata (that characterized by the possession of two gills) is known from the Triassic to the present. The nautiloids are represented today by the chambered nautilus, and the dibranchs by the squids, while the ammonites are extinct.

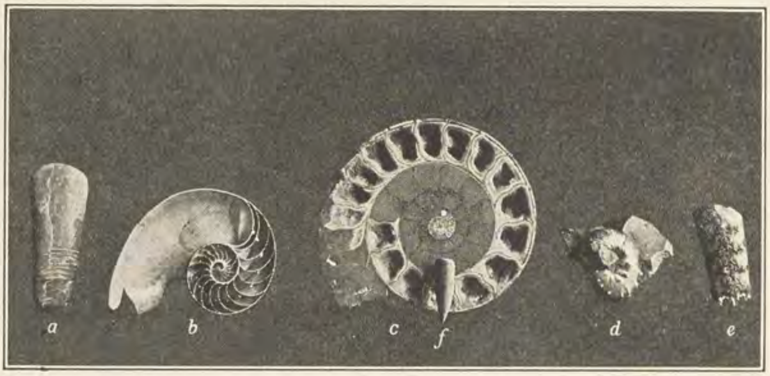


Fig. 124. Cephalopods, all ocean dwellers

a is the straight-shelled Orthoceras living during the Ordovician times in Ohio. The living chamber is above. Note the straight sutures below. The long, gradually tapering lower part of the shell is not preserved. *b* is the chambered nautilus (sectioned) living off the Pacific coasts of North America and Asia. Note the large living chamber and the unused portion of shell partitioned off by successive lime plates. *c* is a section of the Jurassic ammonite Parkinsonia, from England. The living chamber has been broken off. The median whorls and a portion of the outer whorl were filled with mud before the sediment became solidified. The chambers of the remainder are in fact separate geodes, partially filled with crystals of lime carbonate. *d* is the ammonite Scaphites, from Dakota. This was common in the ocean waters covering the interior of North America and its Atlantic shores during the Upper Cretaceous. *e* is the straight-shelled ammonite Baculites, from Montana, coëxtensive with Scaphites. Since the surface shell has disappeared, the fernlike sutures are seen between the mud filling; these sutures are merely the edges of the internal partitions. *f*, the cigar-shaped shell in the center, is the internal skeleton of the Mesozoic squid *Belemnites densus*, from the Jurassic seas of western North America. The specimen is from Wyoming. (Scale: the specimen of Baculites (*e*) is four inches long)

ARTHROPODA

Arising from the annelid worms the arthropods evolved as a most successful group. These, retaining the segmented character of their annelid ancestors, secreted through the skin an external skeleton of chitin completely incasing it. On the inside of this external skeleton muscles were fastened, bringing about a greater precision of activity than in any organism thus far evolved. Their nervous system, built on the same plan as that of the annelids, gives most excellent coördination of the various parts of the body, while the well-developed eyes, the hearing, and the touch organs insure to them a knowledge of food, friend, and foe. But since the external skeleton completely incases the body, growth must be accompanied by a succession of molts. Hence, because of this great waste of energy, these animals can never become of large size. This handicap they have overcome through their hordes of offspring and their accentuation of instinct, with the consequent development of vast social colonies among the highest groups.

Originating as water dwellers during the Proterozoic era, they first become well known to us through the great group of trilobites in the Cambrian at the beginning of the Paleozoic era. Various groups of arthropods show many points of resemblance to the trilobites; these, however, are usually such as point to a common descent but not to ancestral relationship. The trilobites are the most direct descendants of a more primitive group which gave rise also to the eurypterids, limulids, scorpions, centipedes, and phyllopods, and through these to all the higher and later arthropods.

Trilobites. The trilobites (Fig. 125) are the most primitive and generalized representatives of the class Crustacea. They were entirely marine with a trilobed body and usually well-developed compound eyes. They rapidly radiated into bottom-walking forms and rather freely swimming individuals. They reached their maximum in number of species in the Ordovician; by the Devonian the subclass as a whole exhibited the spines characteristic of racial old age, but a few stragglers persisted until the close of the Paleozoic. Trilobites were thus confined to the Paleozoic and during most of this era, judging from the fossil remains, the oceans must have swarmed with them. Over two thousand species, distributed among some two hundred genera, have already been described.

Higher Crustacea. In the Cambrian appear the earliest known representatives of another great group of crustaceans, the *phyllopods* (or branchiopods). This group is either a direct descendant of the trilobites or is descended from its more generalized ancestor. The phyllopods are usually small, often minute, water-dwelling animals. Some of them have developed an extra protective skeleton, the carapace, which in some forms, as Estheria, consists of two laterally placed valves connected by a hinge.

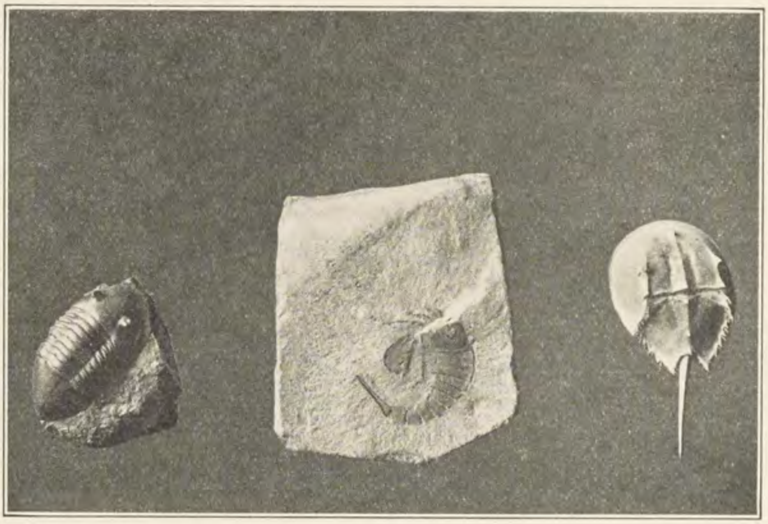


Fig. 125. Arthropods

At the left, a trilobite, *Isotelus gigas*, from New York. It was common in the ocean waters covering much of North America during the Ordovician times. In the middle, the fresh-water or brackish-water Eurypterus, from New York, a mud-grubber of the Silurian time. At the right, the modern horseshoe crab, Limulus, from the Atlantic shores of North America. (Scale: the trilobite is four inches long)

The phyllopods gave rise later to the forms classified as Phyllocarida. Of the phyllocarids only three genera are now living, but they were very abundant during the Paleozoic, the earliest known being from the Cambrian. The phyllocarids radiated during the Paleozoic and later eras into all the higher crustaceans — the marine crabs and lobsters, the fresh-water crayfish, and the terrestrial wood louse and pill bug.

That evolution is not always a forward, upward movement is shown by the *barnacles*, a degenerate group of crustaceans. Frequently the inertia of matter and the difficulties of the environment appear to have discouraged many lower animals, so that they took to the line of least resistance. The ancestral barnacles were free-moving, as is shown in their larval stages, but they early fastened themselves to rocks or other support and then surrounded their bodies with a hard protective skeleton and depended upon chance to bring them food. The earliest known forms, from the Ordovician, have developed merely simple plates upon opposite sides of the body. Later these plates increased in size and strength and interlocked to give greater protection against the beat of the waves. Ruedemann suggests that these Ordovician forms evolved from free-swimming phyllopods.

Arachnida (spiders etc.). *Eurypterids.* The eurypterids (Fig. 125) were one of the earlier offshoots of the ancestral arthropod group. These arose during the uppermost Proterozoic, probably through adaptation to a fresh-water habitat. The gills became concentrated and partially inclosed, forming book gills, between the leaves of which the water circulated. The eurypterids, like the trilobites, persisted from the Cambrian until the close of the Paleozoic.

Scorpions and limulids. Somewhat later but probably from the same ancestral stock arose two other groups. Both have many resemblances to the eurypterids and the trilobites. In each of these two groups book gills developed and the abdomen became much shortened. The group Xiphosura, of which Limulus (the horseshoe crab) (Fig. 125) is the sole survivor, was adapted to a mud-grubbing life in the ocean waters. The other group, that of the extinct water scorpions, had narrow bodies, as is shown by the Silurian Paleophonus etc. These gave rise, probably through the invagination of the book gills to form book lungs, to the land scorpions. (In book lungs the air circulates between the leaves just as water did in book gills.) Later these scorpions apparently developed through various changes, such as the change from book lungs to tracheæ, into the other *air-breathing arachnids* — spiders, daddy long-legs, ticks. (Tracheæ are air tubes held open by elastic spiral threads, penetrating all parts of the body and opening upon the surface of the body in buttonhole-like openings (stigmata). By expansion and contraction of the abdomen air is drawn in and expelled.)

Fig. 126. Stenodictya

A primitive insect from the Pennsylvanian period belonging to the Paleodictyoptera order. The two well-developed wings have a very generalized venation. There is a small extra pair of wings on the prothorax and all the abdominal segments have lateral winglike outpushings, as if all appendages had started with winglike outgrowths but evolutionary laws had selected for survival two anterior pairs. (After Handlirsch from Tothill)

Myriopods and insects. The ancestral arthropod group, or possibly some early trilobite like the Cambrian Olenellus, gave rise to a land branch, the centipedes, through the loss of gills and the development of tracheæ. A similar change occurred in the evolution of the terrestrial isopods (pill bugs etc.) in the higher Crustacea. The later development of the abdominal appendages into wings could produce such generalized insects as the Paleodictyoptera of the Pennsylvanian (Fig. 126).

The insects that lived in the Southern Hemisphere during the incoming of the great glacial period of early Permian time would find their growing season more and more shortened, and hence in some cases too short for complete growth to the adult insect. Those few that survived by some such device as hiding in the earth could continue their interrupted growth the following spring. A habit thus initiated would result in the division of the insect's life into an eating season and an egg-laying season. Such a subdivision of labor would contribute greatly to the survival and multiplication of individuals. Each division of the life period, caterpillar and adult, would develop characteristics necessary to it in its environment independently of the other stage, and thus these two stages would diverge more and more. Some of the steps in such a probable series of change are preserved in insects living today.

CHORDATA, THE HIGHEST ANIMAL PHYLUM

Evolving from an annelid-like stock through the development of a dorsal supporting rod (the notochord, or embryonic backbone) and of a dorsal nerve (the spinal cord) arose the chordates. They gradually discarded the segmented character of the annelids, still seen in the symmetrical arrangement of muscles in such primitive chordates as Amphioxus and lamprey, and in the embryo of sharks etc., and developed an internal protecting skeleton of bone around the spinal cord and its anterior expansion, the brain. Gradually, as necessity arose, anterior and posterior supports, the fore and hind limbs, were evolved, which later became strengthened by an internal bony skeleton. Since this internal skeleton could not be readily modified into implements for different functions (as could the external skeleton of arthropods), a premium was placed upon the development of intellect, so that the few organs might be utilized in a great variety of action. Hence the brain rapidly increased in size.

The evolution of the chordates seems to have proceeded from the annelid stock through a consecutive series of groups which are basically typified by the following ascending series of living forms: tunicates, lamprey eels, ganoid fish, primitive amphibians, reptiles, and mammals. The principal progressive steps that took place during this evolution lay in the nervous system, the internal skeleton, and the method of breathing.

Suggestions of the early stages of the chordates are seen in the early growth stages of the lower groups of vertebrates living today. Abundant fossil remains, from the fish up through the mammals, verify these embryological suggestions as to the succession of forms in earth history.

CLASS 1. TUNICATES

One of the most important of the steps between the annelid worms and the animals with a backbone (vertebrates) may be observed in the larval stages of living marine tunicates (ascidians). The adult tunicate is degenerate, but in the embryo is seen the adult tunicate of ancient days. From such an advanced form as is indicated by the embryo the tunicates have degenerated to the sessile, plantlike tunicates of today; while from some similar form have evolved the higher vertebrates from fish to man. In these ancient forms, as shown by the present embryos, there is the beginning of an internal skeleton; this is a stiffening rod, the notochord, extending through the long tail beneath the principal nerve cord. The notochord is one of the chief characteristics in vertebrates, as is also the presence of gill slits opening into the pharynx. These embryos, looking much like minute tadpoles, both breathe and get their food through the current of water forced through the gill slits.

CLASS 2. AMPHIOXUS

A succeeding step in the direction of the higher vertebrates was some such stage as is seen in the living marine Amphioxus, the lancelet. In this animal the notochord extends from end to end of the body between the spinal cord and the intestine, just as it does in the embryo of all higher vertebrates. The mass of the body is composed of numerous transverse muscle segments by means of which the body can be bent from side to side with great rapidity. Between these segments open the gill slits (homologous to those of the tunicates). Water enters the mouth, urged by cilia lining the gill clefts, passing out by a posterior opening. Breathing is thus performed and feeding also, for a secretion of mucus catches the particles of food in the water current. The blunt anterior end of the spinal cord is the brain; it is no thicker than the rest of the cord but has some of the basal characteristics of the brain of the higher vertebrates.

Amphioxus is the simplest living vertebrate. It has no skull, for with so simple and small a brain it needs none. Its method of getting food and its peculiar gill slits indicate definitely its affinities with the tunicates.

CLASS 3. CYCLOSTOMES

In the lamprey eels the brain is much larger than in Amphioxus, with all the parts typical of higher brains present — cerebrum, cerebellum, medulla oblongata, and, naturally, a skull to inclose it. Eyes are well developed. The number of gill slits is reduced to seven. The notochord has small rods of cartilage attached to its sides and rising so as partially to protect the spinal cord above. These cartilages are the beginnings of the future bony spinal column. Naturally animals with such a primitive cartilaginous skeleton would rarely be preserved fossil. The earliest fossil form, Paleospondylus, which probably belongs here, is from the Devonian.

CLASS 4. FISH

Sharks. The next great advance is seen in the sharks (elasmobranchs). In these the notochord has become entirely surrounded by cartilage developed into a series of biconcave segments (the centra of the backbone) and upward processes surrounding the spinal cord. Since the skeleton is composed almost entirely of cartilage, except in the later and higher sharks, fossil skeletal remains of the older forms are rare and are largely confined to the hornlike fin rays; these are common from the upper Silurian onward. The big-toothed shark Carcharodon (Fig. 75), common in the seas during the Eocene, included the most formidable fish known. One species, *Carcharodon angustidens,* attained, according to Dean, a length of eighty feet.

Development of fins. Certain short, river-dwelling primitive chordates basically allied to the lamprey eels had evolved to a state in which they were capable of responding to the moving water. It seems probable that, developed as a balancing organ, a horizontal fold extended along the sides of the body from the gill slits to the tail, and a median fold extended along the back from the base of the head around the tail. Gradually, to overcome the water current and still aid in balancing, the anterior and posterior portions of the horizontal fin fold became the more developed, becoming the pectoral and pelvic fins (Fig. 127, *a*, *b*). Thus arose the earliest fish, the sharks. Such a probable derivation of the fins is indicated in the embryology of some living sharks as well as in the earliest shark of which the outline is fully preserved, Cladoselache from the upper Devonian of Ohio (Fig. 127, *c*).

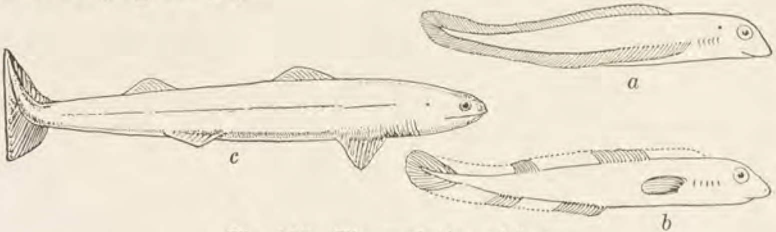


Fig. 127. The evolution of fins

a and *b* represent the probable development of fins as originally balancing organs. In *a*, the more primitive, there is a continuous fin fold upon each side of the body and a continuous dorsal fold. *b* shows the fin fold broken up into distinct fins. Such an origin of fins is apparently supported by the wonderfully preserved shark *Cladoselache fyleri*, *c*, from the Devonian rocks of Ohio. Compare *a* and *c*. (*a* and *b* are from H. W. Shimer, through the courtesy of The Macmillan Company; *c*, from B. Dean)

Ganoids. The ganoids constitute the first step toward a land habitat. Certain plastic lines of individuals of the sharks, living probably during the upper Silurian in the fresh waters of semiarid regions, developed, through various changes, into the ganoids (Fig. 138, *b*). These fish are represented today by river-dwelling forms — the sturgeons from Eurasia and North America, the gar pike (Lepidosteus) and mudfish (Amia) from North America, and Polypterus and Calamoichthys from Africa; the last two genera are the only survivors of the most primitive order, the crossopterygians. During their youthful stage the ganoids have a skeleton of cartilage, as do adult sharks, but this is replaced by bone as the adult stage is reached. This is also true of all higher vertebrates, and thus the central nervous system — brain and spinal cord — is thoroughly protected.

Development of primitive lungs. The ganoids are also characterized by the possession of a primitive lung in addition to the gills. The impetus toward the evolution of a lung would have been especially strong during the dry season, when the fresh waters would become very impure through the decay of plants and animals, and hence a premium would be placed upon the individuals that could gulp a little of the fresher air above the surface of the water in order to supplement that obtained through their gills. Such gulping and holding of the air apparently led to an outpocketing of the pharynx of the throat. Then gradually a muscular control was developed, thus doing away with this gulping of air, and in some forms this air bladder became paired, like the true lungs of the higher vertebrates.

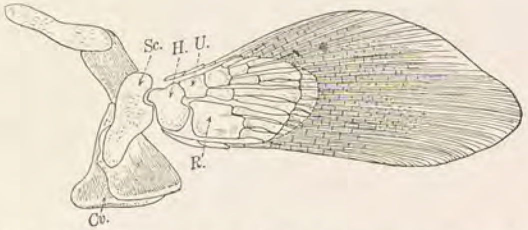


Fig. 128. Pectoral fin of the crossopterygian fish *Sauripterus taylori*, from upper Devonian rocks

Cv., clavicle; *H.*, humerus; *R.*, radius; *Sc.*, scapula; *U.*, ulna. In higher vertebrates, as cat or man, the clavicle is the collar bone; the scapula, the shoulder blade; the humerus, the upper-arm bone; the radius and the ulna, the bones of the forearm. (After W. K. Gregory)

Fins basically limblike. In the primitive ganoids, the crossopterygians, the pectoral and pelvic fins have a fleshy base into which extend offshoots from the cartilaginous backbone. This is especially well marked in fossil forms from the Devonian (Fig. 128). Those cartilages supporting the base of the fins and those forming an attachment to the backbone correspond, bone for bone, to the shoulder and pelvic girdles and the limb bones of all the higher vertebrates, except that the toes had not yet evolved, though even here the division between the great toe and the rest is clearly foreshadowed.

Lungfish (Dipneusti). Another offshoot of apparently the same upper Silurian sharks that gave rise to the ganoids, and evolving probably under the same climatic conditions as the ganoids, are the lungfish (Dipneusti) (Fig. 140, *c*). In these the so-called lungs are better developed than in the ganoids; but they are more primitive in that the notochord persists throughout life and is only partly surrounded by cartilage, and that the cartilage is only slightly hardened by a secretion of bone. The earliest known lungfish are from the Devonian; they were abundant during the upper Paleozoic, but have declined since the early Mesozoic, until today they are represented by only three fresh-water genera, Neoceratodus from Australia, Protopterus from Africa, and Lepidosiren from South America. Neoceratodus, because of its lung, lives easily in waters foul with dead fish of various kinds. Protopterus and Lepidosiren pass the dry season in sleep, caked in mud, and during this time they utilize only their lungs.

Teleosts. The highest type of fish, the teleosts, are merely improved ganoids. Evolving in the early Mesozoic, they have rapidly increased until they are the dominant fish element in all waters. To these belong all the common fish of today. The paired fins have lost the basal fleshy lobe that characterizes the ganoids and the connection of the lung with the gullet has atrophied until it is only an air bladder. But this air bladder is retained as a hydrostatic organ serving to keep the fish of the same specific gravity as the water.

Class 5. Amphibians

The amphibians constitute the second great step toward a land habitat. They apparently developed from the primitive ganoids (crossopterygians) during the Devonian under a continuance of such semiarid conditions as gave rise to the ganoids and lungfish. These earliest of land vertebrates are today represented by the salamanders, frogs, and toads, the salamanders being the most primitive of the three. Apparently the disappearance of pools during the annual dry seasons encouraged certain plastic individuals of the primitive ganoids to utilize the lungs still more, until they became highly vesicular. Since gills are a very grave danger to life in the open air, only those individuals in which they disappeared tended to perpetuate their kind. To withstand the drier air the skin became glandular, secreting a mucus. Thus appeared the earliest fully air-breathing vertebrate. But since the eggs continued to be laid in the old habitat, fresh water, during the rainy season, the young (which are known as tadpoles in frogs and toads) had to develop temporary gills to serve them until lungs and legs were developed and they could leave the water.

Development of limbs. The annual drought would cause the plastic individuals of the primitive ganoids to use the additional support given by their large, fleshy-lobed fins in traveling to more favorable pools. The individuals doing this would stand a better chance of surviving, and hence would pass their increased ability on to their offspring. A continuation of this cause and effect through many thousands of years may possibly have given rise to the jointed limbs of the amphibian. The earliest amphibian footprint known (*Thinopus antiquus*) is from the ripple-marked, mud-cracked sandy shales, of upper Devonian age, of Pennsylvania, and indicates a primitive foot composed of two deeply separated toes, apparently the first digit (great toe) and the second digit. On the outer side of the latter there is evidence of the third and fourth digits, as though they were at this time of earth history in the process of budding out into additional toes until they later became stabilized at five. Such an evolution is apparently corroborated in the ontogeny of the salamander's foot.

In the following period, the Mississippian, normal amphibian footprints are quite common, and a few bones are also known. All Paleozoic amphibians belong to the most primitive order, Stegocephalia (Fig. 138, *c*). These indicate their derivation from the crossopterygian fish, and not from the lungfish, in the similarity of bones of the roof of the skull, the infolding of the walls of the conical teeth, the ring of bony plates surrounding the eye, and the opening (pineal foramen) at the top of the skull. This order, known from the Mississippian to the Triassic, includes individuals with a length of skull of four feet. They were very abundant in the great coal swamps of the upper Paleozoic. The order of salamanders and newts is known from the lower Mesozoic to the present, while the tailless order of frogs and toads has been found from the middle Mesozoic to the present.

Class 6. Reptiles

The reptiles constitute the earliest true land vertebrates. The evolution of the amphibian produced an animal capable of living in the open air though usually restricted to damp regions because of the necessity of retaining a moist skin and of returning to water to lay its eggs. The next step in the evolution of a land vertebrate fauna was the development of an animal not thus tied to water. The impetus to this step may have been the complete disappearance of ponds and streams in some occupied regions, which made aquatic egg-laying impossible. The descendants of the amphibians surviving this radical climatic change developed an egg with a shell which protected it against drying out in the open air, but was also porous so that the developing embryo could breathe. This naturally did away with the necessity of the water, or gill, stage. The resulting animal is the reptile. Such change from an annually very moist region to a drier one would necessitate a change of food, of activities, and consequently of bodily structure. The bones of the skull, for example, became reduced in number and the surface of the body necessarily became completely covered with a layer of scales protecting it from the dry air. (Primitive amphibians, the Stegocephalia, retained the scales inherited from the fish. Even today the cæcilians have many minute scales.) This evolution occurred probably during the upper Mississippian; for the earliest known reptile bones occur in the Pennsylvanian, and by the Permian they were abundant and varied. The world-wide climatic revolution of the late Pennsylvanian and early Permian was probably the stimulus which initiated a great radiation of the reptiles, so that by the opening of the Mesozoic era the principal groups were present. Throughout the entire Mesozoic era reptiles ruled supreme on land, in fresh and marine waters, and in the air. The dominance of the small-brained reptiles throughout the Mesozoic is one of the many still unsolved problems of life; for mammals, with their very much larger brains, had come into existence by the Triassic, but remained insignificant in number and size until the beginning of the Cenozoic.

Beginning with the primitive, generalized, dry-land carnivorous species of the upper Paleozoic, the reptiles rapidly differentiated into those of upland, lowland, swamp, fresh-water, marine, and air habitats, and into those that feed upon flesh, shellfish, and various kinds of plant growth (Fig. 129).

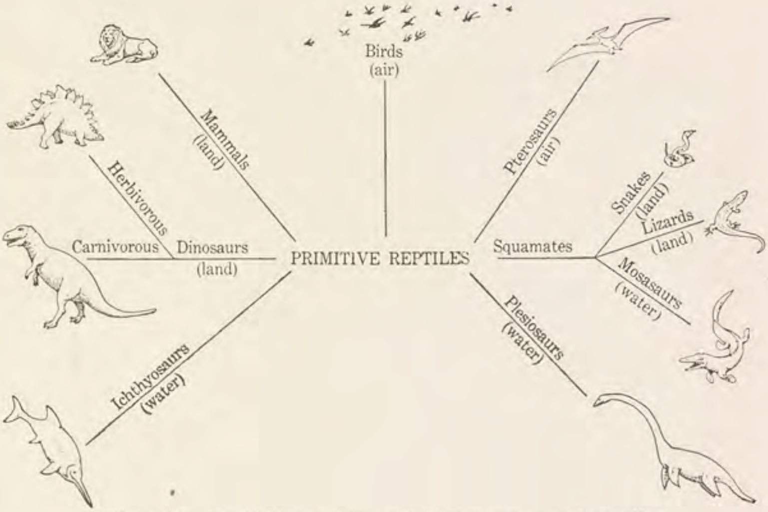


Fig. 129. Radiation of the primitive groups of reptiles

Of the dinosaurs, the herbivorous are represented by the Lower Cretaceous Stegosaurus; the carnivorous, by the Upper Cretaceous Tyrannosaurus

Most orders of reptiles laid eggs, though two and possibly more, retaining the eggs, brought forth their young alive. Dinosaur eggs of several species have been found in the Lower Cretaceous of China (Fig. 130). These are elongated, rounded, and of various sizes; one is 8 inches long and 7 inches in circumference. The shell is about $\frac{1}{16}$ inch thick and was probably hard and not membranous. Some of the eggs are sufficiently developed to show in cross section or by X-ray the delicate bones of the embryonic dinosaurs (R. C. Andrews).

Of the many orders of reptiles, the Cotylosauria, known from the late Pennsylvanian to the Triassic, is one of the most primitive; it embraces characteristics of both amphibians and reptiles.

Dinosaurs. The extinct group of dinosaurs (terrible lizards, as the name indicates) dominated the lands of the earth during the entire Mesozoic. They varied from the size of a sparrow to upward of 30 feet in height and 100 feet in length. Of the two great orders into which they are divided, the Saurischia (pelvic bones crocodile-like) included both herbivorous and carnivorous individuals. Some of the largest herbivorous forms lived in the lagoons of fresh-water swamps. Of these, Brontosaurus (Fig. 138, *d*), living during the Lower Cretaceous in the Rocky Mountain region, had a length of from 60 to 70 feet and an estimated weight of 40 tons; Atlantosaurus, of the same time and place, was probably 80 feet long and 25 feet high; and Diplodocus, with long, snakelike neck and tail but elephantine body, was from 80 to 90 feet long. The carnivorous forms include Anchisaurus and Tyrannosaurus (Fig. 129).

Fig. 130. Dinosaur eggs from Mongolia

The eggs are seen weathering from the base of a cliff. (Photograph through the courtesy of the American Museum of Natural History)

The other great order of dinosaurs, the Ornithischia (pelvic bones birdlike) were herbivorous and had usually birdlike or tortoise-like horny beaks. Some of these, like Trachodon of the Upper Cretaceous of the Rocky Mountain region, walked upon hind feet and were unarmored; others walked upon all four feet and were armored. One of the latter, the 30-foot-long Stegosaurus, living during the Lower Cretaceous in the same region, was protected by huge dorsal triangular plates and tail spines (Fig. 129); another was the three-horned Triceratops, with neck protected by a broad, bony frill (Fig. 89).

Since herbivorous dinosaurs and other available sources of animal food were present, various types of carnivorous dinosaurs with sharp teeth and long claws naturally flourished. These lightly built animals, with hollow limb bones, walked birdlike upon their hind feet, the comparatively short forelegs being held in the air, and apparently were usually rapid runners. Most of the footprints (Fig. 73) upon the Triassic sandy shales of the Connecticut valley were made by this type of dinosaur, such as Anchisaurus. Another genus, Tyrannosaurus, included some of the largest and most terrible land carnivores that ever lived upon earth (Fig. 89).

Plesiosaurs (marine reptiles). Beginning early in the Mesozoic one group of reptiles gradually took to an aquatic life. In the Triassic their limbs are long and slender with the normal number of toes; but by mid-Mesozoic these had changed to true paddles with short bones and many digits; they continued thus to their extinction at the close of the Mesozoic. These paddle-bearing reptiles (Fig. 129) were truly aquatic, producing their young alive; for what appear to be embryos have been found within some. They lived upon fish and such invertebrates as ammonites. To aid in getting this food ready for digestion the animal swallowed stones, as do the grain-eating birds of today. Many such polished gizzard stones (Fig. 131) (in one case half a bushel) have been found with broken bones and shells in that part of the body where the stomach must have been located. At times these stones are a thousand miles from their probable source, giving evidence of the swimming ability of the animals.

Ichthyosaurs (marine reptiles). The dolphinlike ichthyosaurs (Figs. 129, 131) represent another order of aquatic reptiles derived from true land forms. In the individuals living during the Triassic the limb bones were more slender, that is, less paddle-like, than in most of the Jurassic and Cretaceous. Ichthyosaurs were fishlike in form (whence the name) and undoubtedly produced their young alive (from eight to ten at a birth), as these have been found within the fossil parent. Their voracity is attested by the presence in the stomach of one individual of remains of more than two hundred of the ancient squids (belemnites).

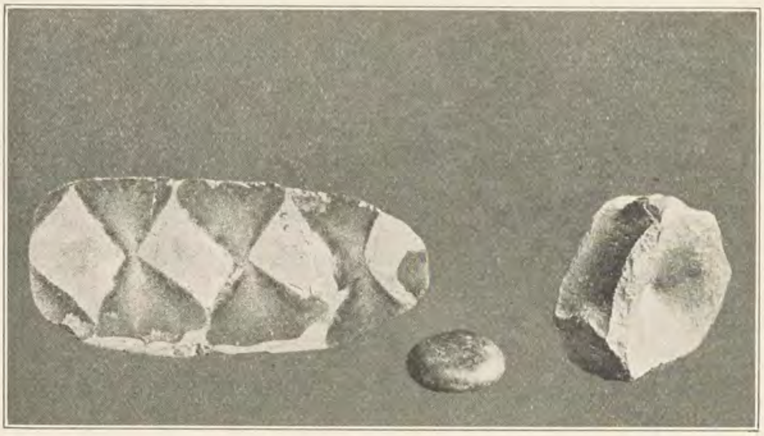


Fig. 131. Ichthyosaur bones from the Jurassic rocks of England

At the right, a single vertebra of the backbone, four inches across; at the left, section through four vertebræ of the backbone inclosed in rock; the cavities between the double concave vertebræ were filled during life with remnants of the notochord. The smooth pebble (two inches long) in the center is one of the gizzard stones used by some ancient reptile (of land or water) as an aid to grinding his food fine; the specimen is from the Lower Cretaceous of Wyoming

Pterosaurs (flying reptiles). The order of pterosaurs (Jurassic to Cretaceous) represents a very successful radiation of the reptiles into the air. The fore limbs of these reptiles are large, batlike wings, the leathery membrane of which is supported between the greatly elongated little finger and the sides of the body. The transition forms from the ancestral reptiles are not yet known; the earliest known fossils, from the Jurassic, are true flying forms. Some of the Cretaceous species became toothless. Pterosaurs, called also pterodactyls, vary in size from that of a sparrow to individuals with a 20-foot spread of wing. Of these larger ones Pteranodon, from the Cretaceous of Kansas, had a skull 30 inches long (Fig. 97).

Crocodiles. The order Crocodilia (Triassic to the present), represented today by crocodiles and alligators, was probably an offshoot of primitive carnivorous dinosaurs.

Chelonia (tortoises, turtles). Protection by horn-covered bony plates, which is common in various orders of reptiles, reaches its maximum in this order. In the dinosaurs protective bones embedded in the skin or as projecting plates of spines covered with horn were common. In the crocodiles this protection was increased by covering both dorsal and ventral surfaces with rows of horn-covered bony plates. In the chelonians horn-covered bony plates are united into one dorsal and one ventral plate, and are joined with the expanded ribs. Between these plates the animal can withdraw head, legs, and tail for protection. The jaws are without teeth and are covered with a horny, birdlike sheath.

Squamata (lizards, snakes). In the order Squamata (Triassic to the present) there is an external protection of horny scales. This includes the lizards, with limbs adapted for walking, the extinct mosasaurs, with limbs modified into swimming paddles, and the snakes, devoid of limbs. The mosasaurs (Fig. 97), evolving from land forms of the Jurassic, were veritable sea serpents and abounded in the seas of the entire earth. Some individuals attained a length of 50 feet or more.

CLASS 7. BIRDS

From the primitive carnivorous dinosaurs there seem to have radiated two very similar types: the one, the birdlike dinosaurs (Ornithischia), stayed on land and became herbivorous; the other, the birds, took to the air and became omnivorous. The many features which these two groups have in common include characters of the foot and of the pelvic (hip) bones, horny beaks, the tendency to use only the hind legs in walking, and a trend toward loss of teeth. The earliest known fossil bird, Archeopteryx (Fig. 138, *e*), from the Jurassic of Europe, is in reality a reptile upon which the scales have developed into true feathers. (Scales are still retained on the legs, however, even in birds of today.) It has numerous sharp teeth in both jaws, claws on each of the three fingers at the tips of its wings, and a long tail composed of about twenty separate vertebræ, to each of which a pair of feathers was attached. Gradually throughout the Mesozoic the birds acquired a more modern appearance; the tail became shortened through the union of the separate bones, and the claws disappeared from the wings. Two well-known birds living in North America during the Cretaceous were the diving bird, Hesperornis, 4½ feet long (Fig. 97), and the small flying bird, Ichthyornis; both had functional teeth. Finally, by the beginning of the Cenozoic, the teeth also had disappeared. The modern era stands for the nonreptilian type of bird as it does for the placental type of mammal. One of the interesting examples of the large flightless ground birds of the Cenozoic was the Diatryma, 7 feet high, a contemporary of the little four-toed horse Eohippus. A nearly entire skeleton has been obtained from the lower Eocene of Wyoming. Its skull is 17 inches long, the huge, elevated, compressed beak is 6½ inches high and 9 inches long, while the lower jaw is correspondingly massive. A much later bird of similar size and appearance, but apparently unrelated, is Phororhachos of South America. A still larger ground bird is the recently extinct Dinornis of New Zealand, which stood 12 feet high.

CLASS 8. MAMMALS

The mammals were apparently derived from an upper Paleozoic order of reptiles, the Therapsida, as this order is intermediate in structure between the stegocephalian amphibians and the lowest existing mammals, the monotremes of the Australian region. Some of the reptiles of this order, the cynodonts, which lived during the Triassic in southern Africa, had the teeth divided into incisors, canines, and molars instead of the typical reptilian uniform series; the lower jaw was composed of one large bone, the dentary, and several small ones, instead of the dentary alone, as in the mammals, or of all small bones, as in typical reptiles. The impelling external cause of this change from reptiles to mammals may have been the aridity and cold of the Permian glacial period with the increased value placed on speed, warm-bloodedness, a covering of hair, and an increased brain development. After their development mammals radiated in various directions in their need of food and protection. Thus there evolved flesh-eating Carnivora, plant-eating Ungulata, gnawing Rodentia, flying Chiroptera (bats), aquatic shallow-water Sirenia (sea cows), and open-sea Cetacea (whales). These variations in food and manner of living were naturally accompanied by changes in form of body and of teeth. The animals developing greater and greater speed would tend to run more and more on their toes, the carnivores necessarily retaining their claws while in the great herbivorous order of ungulates the nail grew part way around each toe, thus forming hoofs. The mammals, as a class, reached their culmination during the Miocene.

Mesozoic mammals (monotremes, marsupials, primitive insectivores). The Mesozoic mammals were small forms, seldom larger than rats. The earliest mammalian fossils known are from the Triassic of North America and Europe. Apparently representatives of only the three lowest orders of mammals evolved during the Mesozoic: the very primitive egg-laying Monotremata, with a body temperature changing normally as much as 15°, according to the temperature of the environment; the more advanced Marsupialia, bearing a pouch for carrying their young, which are born in a very rudimentary condition; and the still more advanced insect-eating and worm-eating Insectivora. The other orders are known fossil first during the early Cenozoic.

The monotremes, restricted today to the Australian region, include the duckbill (Ornithorhynchus) and the spiny anteater (Echidna). The marsupials, with the exception of the American opossum and the South American Cænolestes of carnivorous habits, are also restricted to the Australian region, where they include the kangaroo, wombat, and bandicoot; the insectivores include the moles and shrews.

Chiroptera (bats). The order of bats represents a very successful radiation of mammals into the air. In these animals the fore limb is modified to form a wing between the greatly elongated fingers and the sides of the body and hind limbs. They are known from the Paleocene to the present.

Carnivora. The earliest and most primitive of this flesh-eating order are the creodonts, appearing in the earliest Cenozoic and disappearing in the lower Oligocene. These were, for mammals, small-brained, with poorly developed carnassial teeth (that is, special cutting teeth back of the canines). They could not stand competition with the larger-brained, true Carnivora. The true Carnivora appeared in the upper Eocene and radiated widely, some evolving into the cat family, Felidæ (lion, tiger, leopard, puma, jaguar, lynx, domestic cat), which depend upon a quick spring or a few leaps to get their prey; the dog family, Canidæ (fox, dog, wolf), developed for running down their prey; the weasel family (including the weasel, badger, and skunk); and the flat-footed, climbing bears (Ursidæ) and raccoons, which feed upon plants as well as flesh. One branch of these true Carnivora took to a life in the water; they appeared in the Miocene and are today represented by the seal and walrus.

Rodentia. In one group of large-brained mammals the incisor teeth, and usually only two of these, gradually became enlarged, chisel-shaped, and continually growing. Since the harder enamel was confined to the anterior face of the soft dentine, chisel-like teeth resulted; these were naturally utilized in eating wood and nuts. This type appeared first during the Eocene and has gradually radiated into our modern mice, rats, gophers, rabbits, porcupines, agoutis, capybaras, and the partially aquatic muskrats and beavers.

Edentata. This order of mammals, including the modern sloth, armadillo, and anteater, evolved in South America from the Eocene onward. In these animals the teeth have degenerated until they are weak, without an enamel covering, or entirely wanting. In this order belong also the huge (15 feet long) armadillo-like glyptodonts of the upper Tertiary and the ground sloths, Megatherium and Megalonyx (Fig. 114, *b*), of the same age.

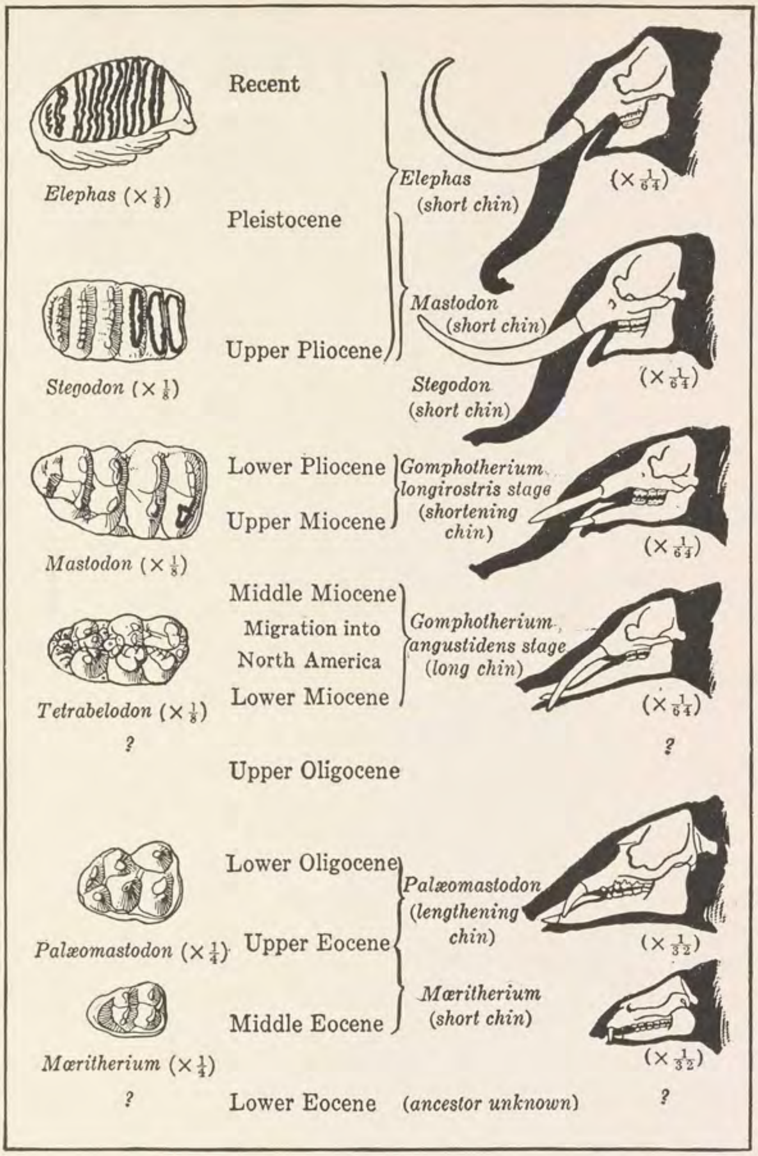


Fig. 132. The probable evolution of the elephant

A single tooth and the corresponding skull are shown in each case. (From Scott after Lull, modified by Sinclair)

Ungulata (hoofed mammals). The branch of mammals radiating to an herbivorous life had no need of canine piercing teeth; hence these tended to disappear (except where, as in the pigs, they were utilized in digging) while the grinding teeth (molars) became larger and the claws changed into hoofs. In the early Eocene it is difficult to distinguish the ancestors of mammals with claws from those with hoofs, and both walked upon the flat of their feet. Later the necessity for speed, in the herbivores to get food and water and to escape their enemies and in the carnivores to capture their fleet prey, led to traveling on the toes. The ungulates include among others the following suborders.

Amblypoda. The members of the extinct suborder Amblypoda, which lived during the Eocene in North America, had small brains and were elephantine in size and build. They include the hippopotamus-like Coryphodon and the giant Dinoceras and Uintatherium.

Proboscidea (elephants). The suborder of elephants, appearing first during the Eocene, evolved from a swamp dweller with a prehensile lip, like Mœritherium of northern Africa. Gradually this lip developed into the trunk, two of the upper incisors became the continually growing tusks (with no enamel covering), one molar on each side above and below increased tremendously in size, and each of the five toes became incased in a hoof (Fig. 132).

Perissodactyla and Artiodactyla. The two best-known suborders of the ungulates are the Perissodactyla, represented by the horse, and the Artiodactyla, represented by the cow, both known from the Eocene to the present. In the former the third toe, from the beginning longer than the other toes, increased more in size, while the side toes became shorter (seen in the living tapir and rhinoceros) until finally, in the modern horse, they disappeared entirely. In the Artiodactyla the third and fourth toes were at first equal in length but longer than the other toes. As with the perissodactyls, the side toes became shorter, as is shown in the living pig, sheep, and deer, and finally disappeared entirely in the modern camel. Both suborders were very prolific in genera, species, and individuals, and abounded on every continent except Australia.

1. *The perissodactyls.* Of these the huge extinct titanotheres (titanic beasts) were of early Tertiary age; some of them attained a length of 15 feet and a height of 8 feet. The tapirs and rhinoceroses are known from early Tertiary times to the present; both were abundant in North America throughout the Tertiary to the Pliocene, when they disappeared from the continent. The rhinoceroses probably evolved in North America, as did the horses.

2. *The evolution of the horse* (Fig. 133). The history of the evolution of the horse is of particular interest both because it is an example of especial adaptation of structure to changing habitat and because it is so well recorded in the strata of successive ages, the ancient river deposits in which the skeletons were buried.

All modern horses are distinguished by the possession of but one toe on each foot, a toe which comparison with other animals shows to be the middle digit of the foot, the hoof corresponding to a nail or claw. Above the toe is a single bone, the cannon bone. This region corresponds to the flat of the foot in plantigrade mammals, as in the bear and man. Behind the cannon bone are two slender little bones, one on each side, called the splint bones. These obviously represent the second and fourth foot bones of other animals.

When the rocks of the ages preceding the present were searched, many bones and even entire skeletons of horses were found, but all differing somewhat from our modern horse. In the Pleistocene the splint bone was longer. In the upper Tertiary (the Miocene rocks) the splint bones were still more lengthened and ended in small toes, but these did not touch the ground and hence could have been of no use. Since the useless side toes of the Miocene horse degenerated into the splint bones of the present one, we should naturally expect to find in an earlier age a time when these side toes were functional. This is the case, for in the Oligocene the horse had three toes touching the ground, though the middle one was longer than the others. In addition to these three toes there is seen on the fore foot a single splint bone similar to those in our modern horse. If the other splint bones indicated the remnants

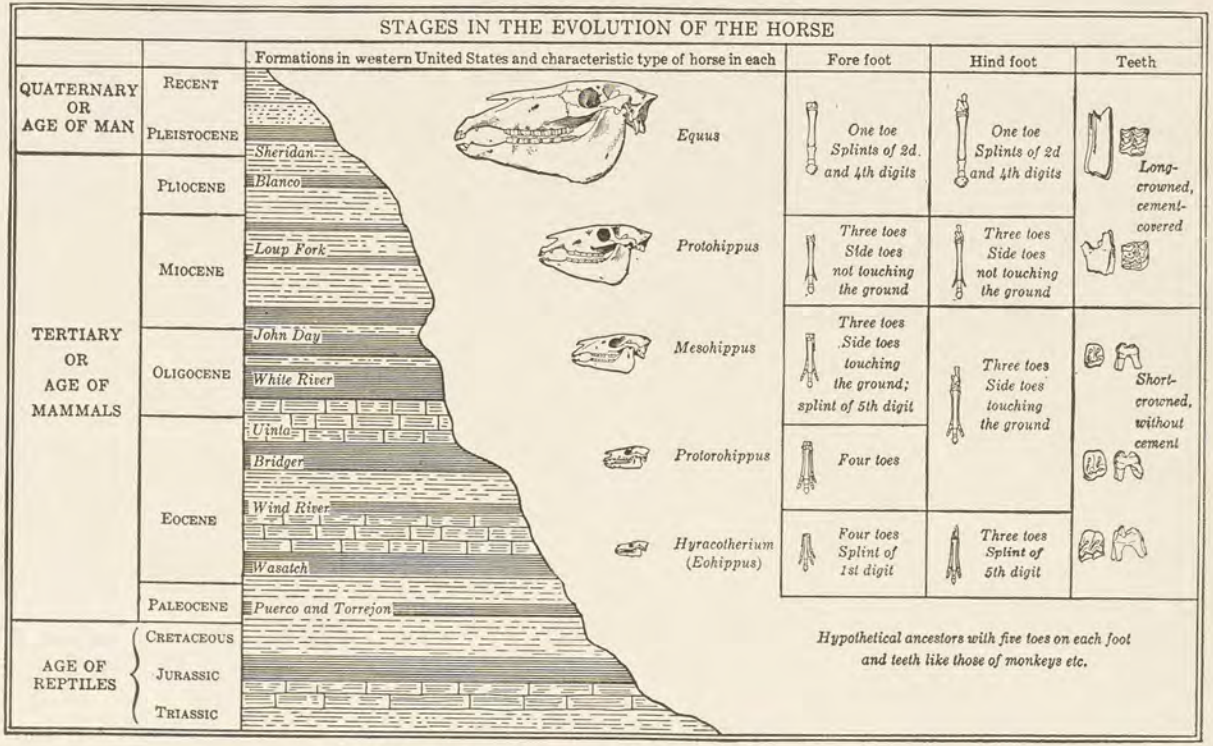


Fig. 133. The evolution of the horse (drawn to scale)

Note movement of eye backwards (hence increase in length of face), decrease in number of toes upon both fore and hind feet, and increase in height of teeth accompanied by the infolding of cement between the enamel ridges. (From W. D. Matthew) of former toes, so should this; and in fact there are found in rocks of an earlier age, the upper Eocene, a horse with four toes on his fore feet and three on his hind feet. Going back still farther in the lower Eocene is one (Eohippus) with four toes on his fore feet, but another splint bone besides, showing that his ancestors must have had five toes. On his hind feet are three toes with a splint of a fourth toe. Five being the normal number of toes in all mammals, it is very probable, from the facts of his known evolution, that the ancestor of this Eocene horse had five toes on each foot (Fig. 134).

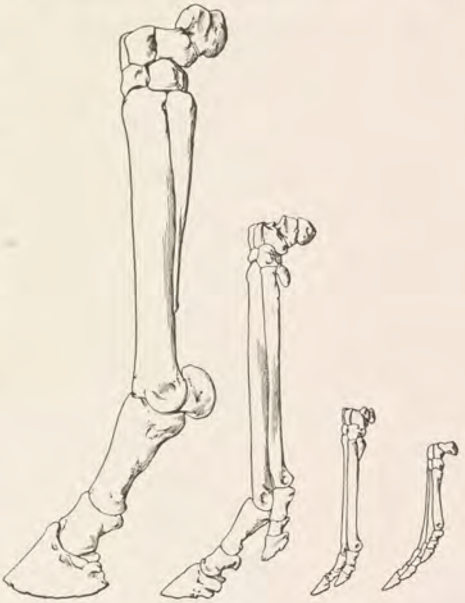


Fig. 134. Principal stages in the evolution of the fore foot of the horse, showing increase in size of the third, or middle, digit and gradual disappearance of the side digits

From right to left: the four-toed Eohippus of the Eocene, the early three-toed Mesohippus of the Oligocene, the later three-toed Merychippus of the Miocene, and the one-toed Equus of the Pleistocene and present. All are outside views showing the middle and outer digits of the fore foot. In Eohippus the two outer toes (digits 4 and 5) are complete. In Mesohippus digit 5 is reduced to a small splint and digit 4 is notably smaller than the middle digit. In Merychippus digit 5 is a tiny nodule of bone and digit 4 has become very slender in comparison with the middle digit. In Equus digit 4 is reduced to a long splint, while of the fifth digit no trace remains. (From W. D. Matthew)

Thus the ancestry of the horse family can be traced back almost to the beginning of the Tertiary. During this long time, variously estimated at from three to fifty millions of years, these animals changed in many ways, especially in feet and teeth. Their evolution can be seen to go hand in hand with the evolution of the plains on which they lived. Little Eohippus was well adapted to western North America of the

Eocene. The region of the present Rocky Mountains and the bordering plains was low ground, as it had just been raised from its ocean bed; it contained many large lakes, aggrading stream beds, and therefore much low, swampy ground. In such a region four toes would stand Eohippus in good stead, to keep him from sinking into the soft ground, just as his small, simple teeth were perfectly adapted to eating the soft, rank herbage of the region. As the ages passed the land rose higher and higher, draining the lakes and swamps, producing broad stretches of open plains. The climate became drier, the forests thinned, and the plains produced less and less grass; and even the grass that remained would be quite dry during much of the year. In the lower Tertiary were many huge animals (titanotheres etc.) that were just as well adapted to their surroundings as was the Eohippus, but their huge, slow bodies and weak teeth did not change to meet the changing surroundings, and consequently they perished. The descendants of Eohippus, however, changed with the changing surroundings. As the country became drier and the ground firmer, and as they had to travel farther and farther for food, speed became more and more necessary. The middle toe was slightly longer than the others, just as our middle finger is the longest, and so, as the ground became harder, the side toes touched it less and less. Hence, as exercise tends to develop and preserve, and the lack of it to destroy, the middle toe became larger and larger, while the side toes became smaller and smaller and finally disappeared, so that today only the splint bones remain as a sort of coat of arms to tell of their ancestry. Just as the hard tire of a bicycle is better for fast riding than the soft one, because less yielding, so the one-toed foot, because less spreading and less yielding, is better for speed on hard ground than is the several-toed foot. The teeth became longer and longer, with the enamel ridges more complex, and finally cement was developed between the ridges of enamel, thus producing a grinder in the true sense of the word, excellently adapted to grinding hard and dry grasses.

Thus, changing with the changing conditions, the horse finally became, as we see it today, one of the most highly specialized animals in its adaptation to its environment. At the end of the Tertiary the continents were more elevated than at present and there was a broad land connection between North America and Eurasia. The horse family spread over the plains of all continents except Australia. For some unknown reason the family died out in both North and South America at the close of the Pleistocene, and on the western plains of North America its place was taken by the immense herds of bison. The horse had thus disappeared from the New World before the white man invaded it. The wild horses in America today are descendants of horses brought in by the Spaniards and other early settlers.

3. *The artiodactyls.* The artiodactyls include among others the pigs and peccaries, which are the least modified of the ancestral artiodactyls, the hippopotamus, the very abundant and entirely North American oreodonts (confined to the Tertiary), the camel, giraffe, deer, sheep, goat, chamois, and ox, including domestic cattle. The family of camels (camel, llama) evolved apparently upon the continent of North America from primitive upper Eocene forms. Influenced by the same environmental causes, they passed through the same kind of structural changes as did the contemporary horses. There was an increase in the size of the body, from that of a jack rabbit to individuals larger than the living Bactrian camel, a relative increase in length of foot over the foreleg, a reduction in number of toes from five to two, and a change from low-crowned browsing teeth to high-crowned grinding teeth. During the Pliocene the camels migrated to South America, Asia, and Africa, where they still survive, but they disappeared from their native home during the Pleistocene.

Sirenia. The existing sea cows have a fishlike body, fore limbs paddle-like, a horizontally expanded tail fin, and no hind limbs, though vestiges of hip bones are present. This order of herbivorous mammals is represented today by the dugong, inhabiting the Indian Ocean, and the manatee, living in the rivers about the Gulf of Mexico and western Africa. They have apparently evolved from the same ungulate stock as the elephants, that is, from a form closely allied to the Eocene

Mœritherium of North Africa. The earliest fossils are from the Eocene of Egypt and the West Indies.

Cetacea. The whales have adapted themselves to a life in the ocean more completely than have any of the other mammals. They are probably descended from land-dwelling Carnivora. The primitive whales, the zeuglodonts, apparently abundant during the Eocene in the seas throughout the world, are transitional in certain characteristics to the primitive Carnivora. Today the toothed whales include among others the dolphin, porpoise, narwhal, and the sperm and beaked whales; the whalebone whales include the gray, fin, and right whales.

Primates. The mammals in this order have been derived from the Insectivora. They represent a branch which took to a life in the trees. They are distinguished from other mammals by a combination of characters, chief of which are the following: fore limbs adapted for grasping; usually five digits provided with flat nails; a large and highly developed brain; two mammary glands. Man differs from his nearest relations, the anthropoid apes, especially in (1) the greater development of the cerebral portion of the skull, and the corresponding reduction of the jaws, that is, a development of the thinking, reasoning part of the brain and a decrease in the length of the jaws and associated face connected with animal functions, a development correlated with (2) the greater size and complexity of the brain; (3) the perfectly erect attitude correlated with (4) the more complete adaptation of the hind limbs to bearing the weight of the body; (5) the nonopposable hallux (great toe), and the more opposable pollex (thumb); (6) the possession of articulate speech; (7) self-consciousness and the power of abstract reasoning.

Of the two groups composing the order, the more primitive, the lemurs, are known from the Paleocene to the present. The higher group, the anthropoids, separating from the lemurs during the Eocene if not earlier, are represented today by the broad-nosed monkeys of America, the narrow-nosed monkeys of the Old World, the anthropoid apes of the same region, and man.

Records of man (Table XVII). The presence of man upon earth is being recorded today as it was in the past. In swamps,

TABLE XVII. CHART SHOWING IN BRIEF THE SUCCESSIVE STAGES OF MAN AND HIS CULTURES FROM THE EARLIEST KNOWN REMAINS TO HISTORIC TIMES, CORRELATED WITH THE VARYING CLIMATIC EPOCHS AND ESTIMATED TIME IN YEARS

	CLIMATIC CONDITIONS	MAN	CULTURES	ARCHEOLOGICAL DIVISIONS		TIME ESTIMATE FOR EUROPE
HOLOCENE	Completion of oceanic depression to present level (climate as today)	*Homo sapiens*: Modern	Conquest of Gaul by Cæsar Iron in current use in Egypt and Chaldea about 1350 B.C.	Age of Metals	Iron	B.C. 50 500 900
	Gradual rise of depressed lands and depression of marginal bulge (climate warmer than today)		First bronze objects in Egypt and Chaldea about 3500 B.C.		Bronze	2000
	Ocean waters flooding depressed lands		Neolithic culture began in southwest Asia about 18,000 B.C.	Age of Stone	Neolithic	7500
PLEISTOCENE	Ice front retreated to southern Sweden	*Homo sapiens*: Ancient (Cro-Magnon race etc.)	Magdalenian Solutrean		Paleolithic	
	Würm (Wisconsin) glacial advance		Aurignacian			15,000
	Interglacial (warm faunas)	*Homo neanderthalensis*	Mousterian			20,000 50,000
	Riss (Illinoian) glacial advance					
	Interglacial (warm faunas)		Acheulian			
	Mindel (Kansan) glacial advance	*Homo heidelbergensis*	Chellean			
	Interglacial (warm faunas)		Cromerian			400,000
	Günz (Nebraskan) glacial advance					500,000 to
PLIOCENE	Warm faunas		Foxhallian			1,000,000

in sediment deposited by flood-time rivers, in lakes and oceans, under the products of volcanic explosions, and in land areas sunk beneath the surface of the ocean, skeletons of man or the products of his handicraft are being preserved. From the character of these remains an estimate of his physical, mental, and social development can be gained.

Paleolithic Age. In Europe, where the epochs of man's early history have been best studied, the earliest record of his presence is evidence of fire in association with such implements as very crude stone spearheads. Such remains have been found at Foxhall, Ipswich, in southeastern England, and are associated with typically upper Pliocene elephants and other animals. During the succeeding Pleistocene, evidences of man's handicraft, as well as his skeletal remains, are increasingly numerous. These represent several very distinct cultures, the later showing great advances over the earlier in the efficiency of weapons and tools. The Aurignacian culture developed artistic ability of a high degree, as is shown by carvings on ivory and paintings on the walls of caves.

All these earliest records indicate dominantly stone cultures; that is, the tools and weapons were made of stone. These stones were merely chipped and not smoothed, and the period which they characterize is called the Paleolithic, the Older Stone Age. This stage continued in Europe until some time after the last glacial advance had retreated to the higher lands, that is, until after the close of the Pleistocene.

Neolithic Age. Successive invasions from Asia brought into Europe men with a higher type of culture. These people still belonged to the Stone Age, but most of their tools and weapons were of smoothed and polished stone, forming much more efficient implements. These men of the Newer Stone Age (Neolithic) brought with them also the beginnings of agriculture, the art of making pottery, and the domestication of animals. They evidently drove out the preceding races, as their cultural remains are found superposed upon the Paleolithic all over Europe. Some of them built villages on piles in lakes some distance from the shore. In the lakes of Switzerland evidences of many such dwellings have been found.

Bronze Age. Gradually man learned the use of metals. Copper was apparently the first to be utilized, but the harder bronze, an alloy made chiefly of copper and tin, soon supplanted it in popularity.

Iron Age. Later the smelting of iron was developed, and owing to the abundance of this metal and its widespread use material civilization advanced very rapidly.

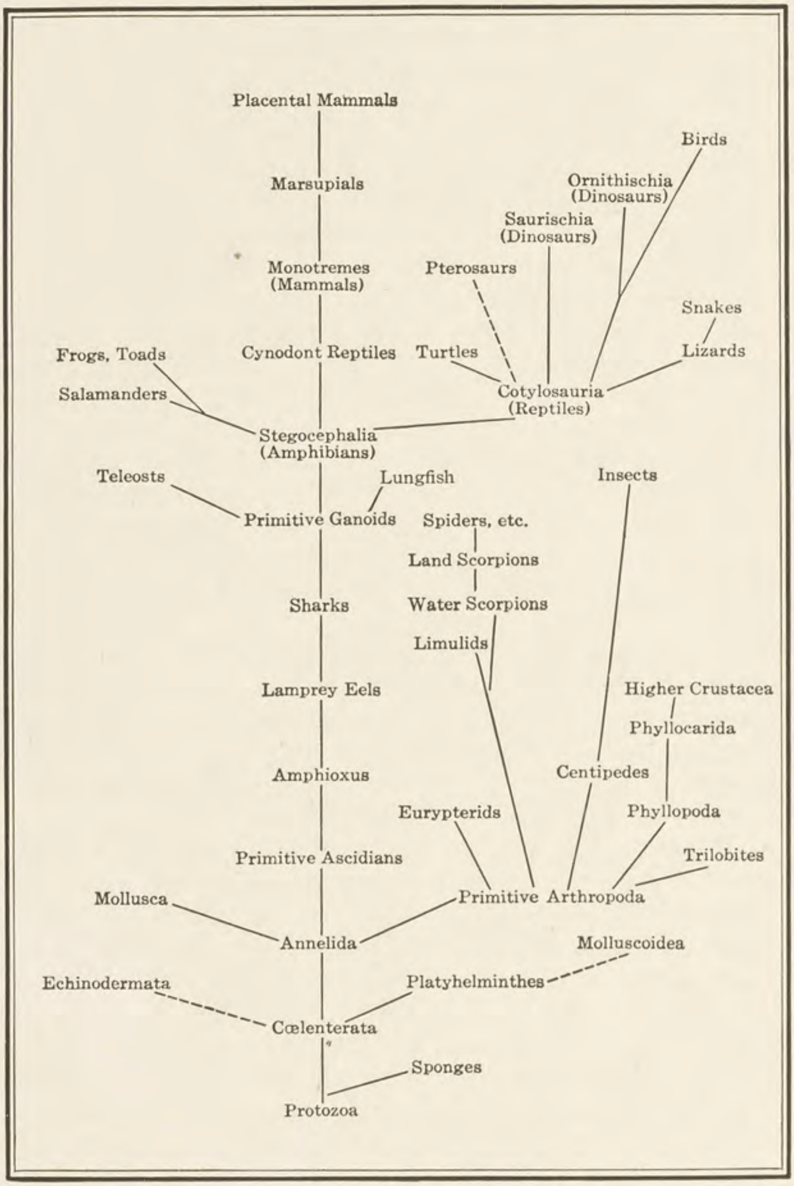
Implements of the Bronze Age are found above the remains of Neolithic man in the deposits formed beneath the villages of the lake dwellers, while resting upon the remains of the Bronze Age occur primitive implements of the Iron Age, showing that these well-protected lake dwellings were occupied continuously for very long periods.

Man in North America. No undoubted remains of man in North America are known from the Pleistocene or earlier, but stone weapons are found associated with such extinct animals as the mastodon and the giant sloth, which lived immediately after the final retreat of the glaciers from the United States (p. 283).

SUMMARY OF EVOLUTION OF LAND ANIMALS

Among the lines of variation to be noted in the evolution of the higher animals are: (1) increasing independence of external water through the evolution of air-breathing organs and a supporting skeleton adapted to use on land or in air; (2) gradual development of a more and more complex and centrally controlled system of nerves resulting in a more efficient coördination of the increasingly efficient muscles and other body organs; (3) ever-increasing protection of the new generation by the parent animal. The earliest animals were tied to the water; it kept them from drying up and usually brought them food. The transition landward was made by many different groups, the most important of which are spiders, insects, and the vertebrate line. Of this last group the ganoid fish took the first definite step landward; this was continued by the amphibians and completed by the reptiles. The line of evolution to the mammals begins, as does that of all other lines, with the one-celled protozoön; all higher animals begin growth with this

TABLE XVIII. EVOLUTIONARY TREE OF ANIMALS



one-celled stage. A primitive many-celled type, somewhat similar to that seen in the sponge, must have preceded the cœlenterate, though the sponge as we know it cannot be in the direct line to any of the higher animals. In the cœlenterate both nerves and muscles are developed, but they are short and slow in response. With the evolution of a central nervous system extending the length of the body there began, in the next great group, the annelid worms, a more rapid response of the animal to its environment. Next, the development of an elongated supporting rod, the notochord, brought into existence the Chordata, the highest animal phylum. The notochord is well developed in the larvæ of the degenerate ascidians and so must have been present in the adults of their ancestors; these forms also possess gills. About the notochord and extending above it so as gradually to inclose the spinal cord, later animals developed the backbone, made up of separate pieces, or vertebræ (whence the name *vertebrates*). From the arches supporting the gills are evolved the jaws and a few bones of the head and neck of the higher vertebrates; for a structure once evolved is usually retained though in a form modified to suit changed conditions. In Amphioxus, although the brain is no larger in diameter than is the spinal cord, it contains some of the basic elements of the brain of all higher vertebrates. From Amphioxus to the highest mammals the brain exhibits a gradually ascending series of changes. The lamprey eels (Cyclostomata) possess a series of cartilages, arising from the notochord, which may be considered as the beginnings of the backbone. Gradually in the fish and amphibians these cartilaginous outgrowths more and more completely surround the spinal cord as well as the notochord itself. Finally, in the series of vertebrates beginning in the sharks and ascending to the mammals, the cartilage is increasingly replaced by bone. Embryos of higher animals pass through these stages of lower animals during their growth. In the sharks are first seen the upper and lower jaws, evolved from the anterior gill arches of primitive lamprey eel-like forms. The lamprey eels do not possess jaws, but merely a sucking mouth. The animals of the succeeding group, the ganoid fish, possess in addition to the gills a primitive lung, by means of which they can derive fresh air from above the surface of the waters when these are impure. In the amphibians the gills are present only during the larval (tadpole) stage, after which the animal breathes entirely by lungs; it also develops limbs (arising from the pectoral and pelvic fins of its ganoid ancestors). The amphibians, however, still lay their

TABLE XIX. EVOLUTIONARY STAGES LEADING TO MAMMALS

	LAND DWELLERS (A FEW SECONDARY WATER DWELLERS)	WATER DWELLERS	EARLIEST RECORDED APPEARANCE	COMMON NAME OR LIVING EXAMPLE
VERTEBRATES	Eggs retained within the mother. Young nourished after birth		Early Mesozoic	Mammals
	Eggs laid on the land. Abdominal breathing organs		Late Paleozoic	Reptiles
	Lungs in adult. Gills in youth		Middle Paleozoic	Amphibians
	Primitive lungs besides gills		Middle Paleozoic	Ganoid fish
		Anterior gill arches modified into jaws	Middle Paleozoic	Sharks
		Beginnings of backbone arising from notochord to protect spinal cord	Middle Paleozoic	Lamprey eels
		Basic elements of brain of higher vertebrates		Amphioxus
INVERTEBRATES		Supporting rod (notochord) and gills		Ascidians
		Central nervous system	Proterozoic	Annelid worms
		Primitive nerves and muscles	Early Paleozoic	Cœlenterates
		Colonial		Some protozoöns
		Reproduction by simple subdivision, by spores, and by union of sex cells	Proterozoic	Protozoöns (one-celled)

TABLE XX. TABULAR VIEW OF THE ANIMAL KINGDOM

Phyla and classes are arranged from the simple and more primitive
(below) to the higher and more complex (above)

PHYLUM	CLASS		KNOWN RANGE	COMMON NAME OR LIVING EXAMPLE
XII. Chordata	VERTEBRATA	Mammalia	Triassic to present	Mammals
		Aves	Jurassic to present	Birds
		Reptilia	Pennsylvanian to present	Reptiles
		Amphibia	Devonian to present	Amphibians
		Pisces	Silurian to present	Fish
		(?) Ostracodermi	Ordovician through Devonian	Shield fish
		Cyclostomata	Devonian (?) to present	Lamprey eels
		Acrania	(Fossil record lacking)	Amphioxus
	INVERTEBRATA	Urochorda	(Fossil record lacking)	Ascidians
		Adelochorda	(Fossil record lacking)	Balanoglossus
XI. Arthropoda		Insecta	Pennsylvanian to present	Insects
		Arachnida	Cambrian to present	Spiders
		Myriopoda	Devonian to present	Centipedes
		Onychophora	Cambrian (?) to present	Peripatus
		Crustacea	Cambrian to present	Lobsters
X. Mollusca		Cephalopoda	Cambrian to present	Nautilus
		Scaphopoda	Ordovician to present	Tooth shells
		Gastropoda	Cambrian to present	Snails
		Pelecypoda	Cambrian to present	Clams
		Amphineura	Ordovician to present	Chitons
IX. Molluscoidea		Brachiopoda	Cambrian to present	Brachiopods
		Phoronida	(Fossil record lacking)	Phoronis
		Bryozoa	Ordovician to present	Bryozoans
VIII. Echinodermata		Holothurioidea	Cambrian to present	Sea cucumbers
		Echinoidea	Ordovician to present	Sea urchins
		Ophiuroidea	Ordovician to present	Brittle stars
		Asteroidea	Cambrian to present	Starfish
		Crinoidea	Ordovician to present	Sea lilies
		Blastoidea	Ordovician to Permian	Sea buds
		Cystoidea	Cambrian to Permian	Cystoids
VII. Annulata		Classes are omitted	Cambrian to present	Segmented worms
VI. Trochelminthes			(Fossil record lacking)	Wheel worms
V. Nemathelminthes			Cambrian (?) to present	Threadworms
IV. Platyhelminthes			Pennsylvanian to present	Flatworms
III. Cœlenterata		Ctenophora	(Fossil record lacking)	Comb jellies
		Anthozoa	Proterozoic to present	Corals
		Scyphozoa	Cambrian to present	Jellyfish
		Hydrozoa	Cambrian to present	Hydrozoöns
II. Porifera		Spongiæ	Proterozoic to present	Sponges
I. Protozoa		Infusoria	(Fossil record lacking)	Infusorians
		Sporozoa	(Fossil record lacking)	Gregarina
		Sarcodina	Proterozoic to present	Amœba
		Mastigophora	Cretaceous (?) to present	Euglena
		Choanoflagellata		
		Flagellata		
		Mycetozoa	(Fossil record lacking)	Slime molds
		(*Myxomycetes*)		

eggs in the water. The final step landward was taken by the reptiles; these evolved a porous shell surrounding each egg, which was laid upon land. They also developed abdominal breathing organs; hence the animal need no longer swallow its air, as do the amphibians and ganoids. These breathing muscles the reptiles passed on to their descendants, the mammals. Finally, in the typical mammals the eggs are retained by the mother during the early development of the embryo, and after birth the young are further nourished and protected by the mother for a variable time — a time which increases in the higher placental mammals. The living mammals are divided into: (1) the very primitive monotremes, in which mammary glands are devoid of teats; (2) the transitional marsupials, in which the young are born in a rudimentary condition; and (3) the placental mammals, in which the young are nourished in the uterus for a long period through the agency of a placenta. Placental mammals include all living mammals except the monotremes and marsupials.

TOPICAL REVIEW

- Protozoa, comprising unicellular animals
- The development of multicellular animals
- Sponges
- Cœlenterata
- Worms
- Echinodermata
- Molluscoidea
- Mollusca
- Arthropoda
  - Trilobites
  - Higher Crustacea
  - Arachnida
    - Eurypterids
    - Scorpions and limulids
  - Myriopods and insects
- Chordata, the highest animal phylum
  - Class 1. Tunicates
  - Class 2. Amphioxus
  - Class 3. Cyclostomes

- Class 4. Fish
  - Sharks
    - Development of fins
  - Ganoids (the first step toward a land habitat)
    - Development of primitive lungs
    - Fins basically limblike
  - Lungfish (Dipneusti)
  - Teleosts
- Class 5. Amphibians (the second step toward a land habitat)
  - Development of limbs
- Class 6. Reptiles
  - Dinosaurs
  - Plesiosaurs (marine reptiles)
  - Ichthyosaurs (marine reptiles)
  - Pterosaurs (flying reptiles)
  - Crocodiles
  - Chelonia (tortoises, turtles)
  - Squamata (lizards, snakes)
- Class 7. Birds
- Class 8. Mammals
  - Mesozoic mammals (monotremes, marsupials, primitive insectivores)
  - Chiroptera (bats)
  - Carnivora
  - Rodentia
  - Edentata
  - Ungulata (hoofed mammals)
    - Amblypoda
    - Proboscidea (elephants)
    - Perissodactyla and Artiodactyla
      - The perissodactyls
      - The evolution of the horse
      - The artiodactyls
  - Sirenia
  - Cetacea
  - Primates (lemurs, monkeys, apes, man)
    - Records of man
      - Paleolithic Age; Neolithic Age
      - Bronze Age; Iron Age
      - Man in North America
- Summary of evolution of land animals

CHAPTER XX

SUMMARY OF PLANT AND ANIMAL LIFE

The progressive variation of life. It is supposed that life first appeared on earth in the form of minute masses of protoplasm during the earliest era of earth history, the Archeozoic. Gradually it developed the heredity-bearing nucleus, and through the development of chlorophyll it became able to gain its necessary energy by trapping some of the sun's rays. Some organisms tending to become fixed to the earth emphasized the securing of energy from the sun, while others tending to go in search of their food emphasized movement. The former became the plants, the latter the animals (Fig. 135). Gradually and continuously from the Archeozoic to the present both plants and animals have radiated in various directions where food and protection were available and reproduction possible. In their history on earth both plants and animals, beginning life in the water, passed through an amphibious stage to the present dominant land stage. This development is shown in Fig. 136.

The lower invertebrates, dominant on the earth during the early Paleozoic, include the more primitive representatives of every phylum. The higher representatives appeared later; each phylum after its establishment became a separate center of evolution, radiating into various habitats permitted by its stage of development. Thus, the higher pelecypods, those better protected through a well-developed hinge plate and siphons, though appearing with a few of the simpler representatives during the Paleozoic, did not become important in number of families until the Mesozoic; they are the dominant forms today. Of the higher crustaceans the order Decapoda, which includes the crayfish, lobster, and crab, is known first from the Triassic. Of the arachnids, the order of true land spiders begins in the Pennsylvanian, as does also the order of

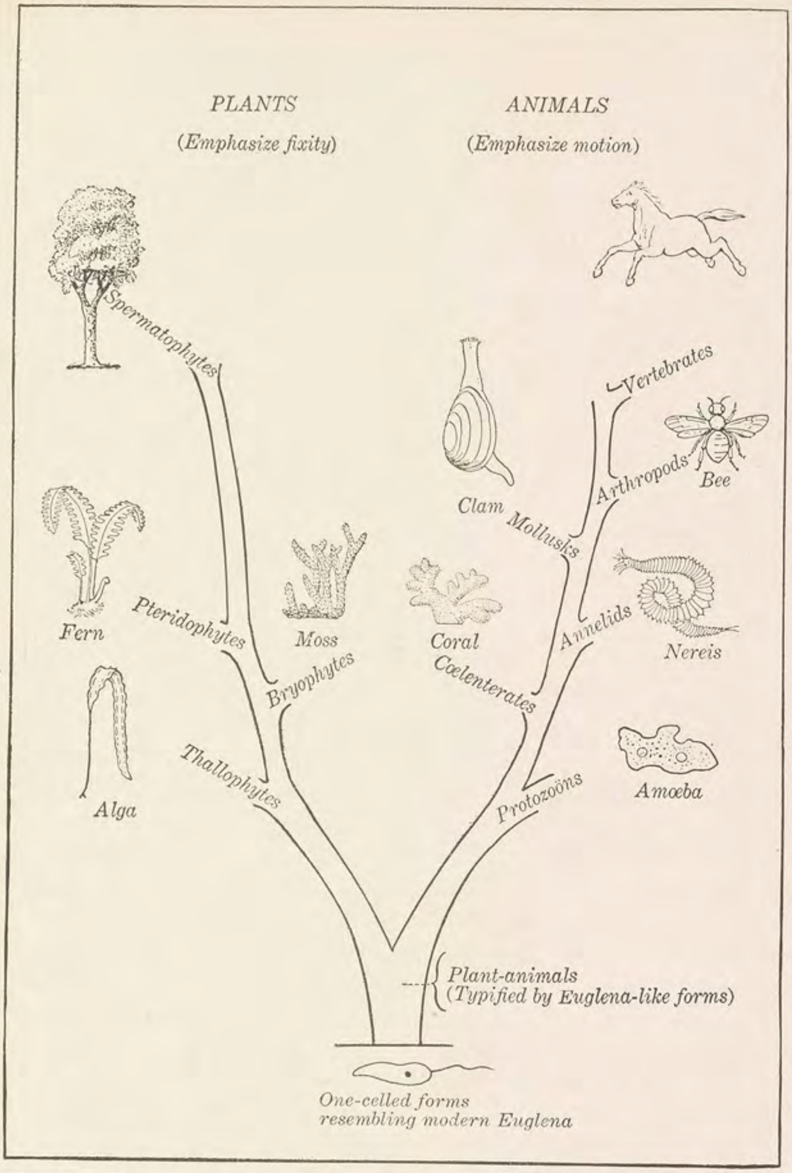


Fig. 135. Diagram to illustrate the initial division of the life force into plants and animals and its repeated further branching into progressively higher and higher phyla. Only six of the twelve phyla of animals are represented

the daddy longlegs. The highest class of the arthropods, the insects, is known first from the Pennsylvanian, though represented only by such low families as the cockroaches, while, of the higher orders, the beetles (Coleoptera) make their appearance in the Triassic, and the butterflies and moths in the Jurassic.

Of the vertebrates the earliest important class to make its appearance was that of the fishes. Rapidly radiating into sharks, ganoids, and lungfish, they became the dominant element in the waters of the middle and late Paleozoic. Arising from the ganoid fish during the Devonian, the amphibians took possession of the swamp lands and were very abundant in the coal swamps of the later Paleozoic, while, evolving from the amphibians during the Pennsylvanian, the reptiles spread over the drier lands of the earth. Thus by the later Paleozoic these three realms — water, swamp, and dry land — were under control of the vertebrates. The air was as yet conquered only by the insects.

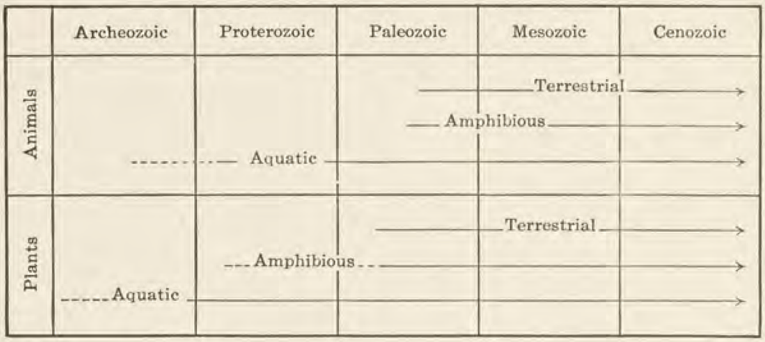


Fig. 136. Succession of primitively aquatic, amphibious, and terrestrial plants and animals

Of plants, the aquatic include algæ, the amphibious comprise liverworts, mosses, ferns, horsetails, and club mosses, and the terrestrial, seed-ferns, conifers, and flowering plants. Of animals, the aquatic comprise fish and all invertebrates except some such high groups as insects; the amphibious include salamanders, frogs, and toads; and the terrestrial, reptiles, birds, and mammals. Some of the terrestrial forms of both plants and animals may take secondarily to an aquatic life, but evidence of their terrestrial ancestry is always preserved, as, for example, lungs in whales and true seeds in the water lily

Throughout the Mesozoic the reptiles not only continued to dominate the lands but radiated into certain forms (the pterosaurs) which seized control of the air, into others (the crocodiles and similar forms) which dominated the swamps, and into others (ichthyosaurs, plesiosaurs, mosasaurs) which competed with fish for the supremacy of the seas. The birds first appeared during the Jurassic, but did not become dominant until they had discarded teeth, wing claws, and long vertebrated tail. Since the beginning of the Cenozoic they have held the supremacy of the air.

The mammals, known first from the Triassic, remained like the birds in a subordinate position until, by the beginning of the Cenozoic, they had evolved the highly intelligent type of modern mammal; since then they have become supreme on land and sea. The highest of the mammals, man, is first definitely known from the Pliocene of the Tertiary. Since that period he has been gradually gaining dominancy over all other forms of life. Today his struggle for supremacy is most keen with the insects and the parasites which they carry.

New groups of plants and animals either develop an ability to live in regions hitherto unoccupied or to overcome other life already there. Thus, the liverworts, ferns, and amphibians developed an ability to live in the hitherto unoccupied swamps, as later the gymnosperms and reptiles occupied the drier lands. Still later the flowering plants and mammals forced their way to dominancy over the others. The dominant forms do not, as a rule, exterminate the others, but by appropriating the more desirable habitats force them into less desirable regions. This change in supremacy is always, however, an advance in type of organization. Thus, the dominance of the brainless invertebrates gave way to that of the brain-bearing fish and amphibian, as later the brute force of the small-brained reptile yielded to the much higher mentality of the mammal.

It is thus seen that the life of the earth has increased in complexity (Figs. 136, 137). If man had been living during the Cambrian, he could have studied only the lowest plants, such as algæ, and probably liverworts, and among animals only the lower invertebrates. In the later Paleozoic he would have seen in addition such plants as ferns and primitive seed-bearing plants, and such animals as insects, fish, amphibians, and primitive reptiles. In the later Mesozoic he would also have seen the higher seed-plants, higher reptiles, and primitive birds and mammals. Today we have a tremendous assemblage of organisms, the accumulation of ages of evolution. While many primitive groups have disappeared through the vicissitudes brought about by changes in the earth's surface and by competition with other forms, yet the majority of larger groups still have living representatives; that is, the groundwork of each of the various groups remains very much as it was at its establishment, but the specific expression in individuals is always changing. Thus, for example, though brachiopods have been present from the Cambrian to the present, the species found in the various periods are different, and so it is with all other groups.

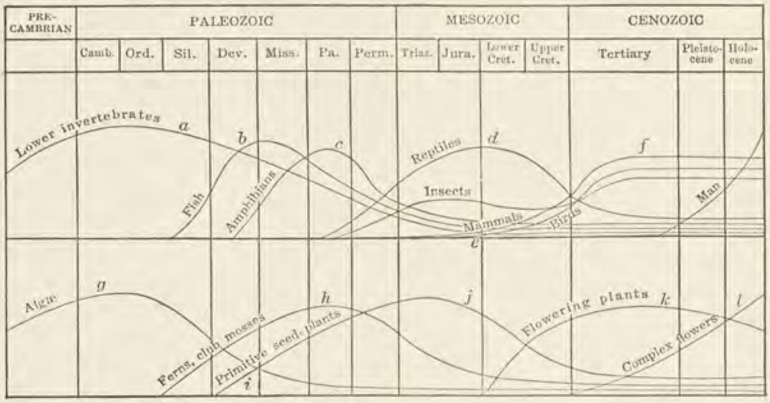
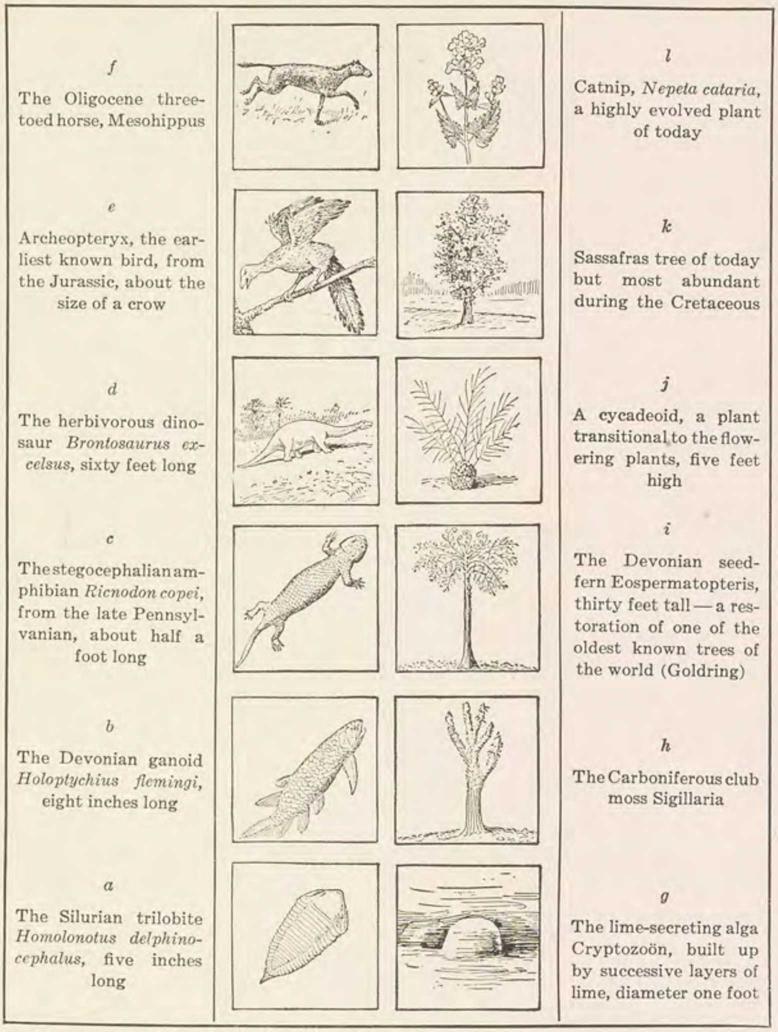


Fig. 137. The increasing complexity of life

Showing the gradual incoming of successively higher groups of animals and plants

Physical changes at the earth's surface produce changes in life. Since today among plants and animals the principal external force that urges toward change is necessity, it was presumably so throughout the past history of these organisms,— an external force that brings out a more or less adaptive response from within the individual. Hence, for an understanding of the adaptive changes that are displayed by organisms as they have evolved through the ages, the changes which the earth



f

The Oligocene three-toed horse, Mesohippus

e

Archeopteryx, the earliest known bird, from the Jurassic, about the size of a crow

d

The herbivorous dinosaur *Brontosaurus excelsus*, sixty feet long

c

The stegocephalian amphibian *Ricnodon copei*, from the late Pennsylvanian, about half a foot long

b

The Devonian ganoid *Holoptychius flemingi*, eight inches long

a

The Silurian trilobite *Homolonotus delphinocephalus*, five inches long

l

Catnip, *Nepeta cataria*, a highly evolved plant of today

k

Sassafras tree of today but most abundant during the Cretaceous

j

A cycadeoid, a plant transitional to the flowering plants, five feet high

i

The Devonian seed-fern Eospermatopteris, thirty feet tall — a restoration of one of the oldest known trees of the world (Goldring)

h

The Carboniferous club moss Sigillaria

g

The lime-secreting alga Cryptozoön, built up by successive layers of lime, diameter one foot

Fig. 138. Illustrative examples of the life waves shown in Fig. 137 arranged in the order of their appearance upon earth

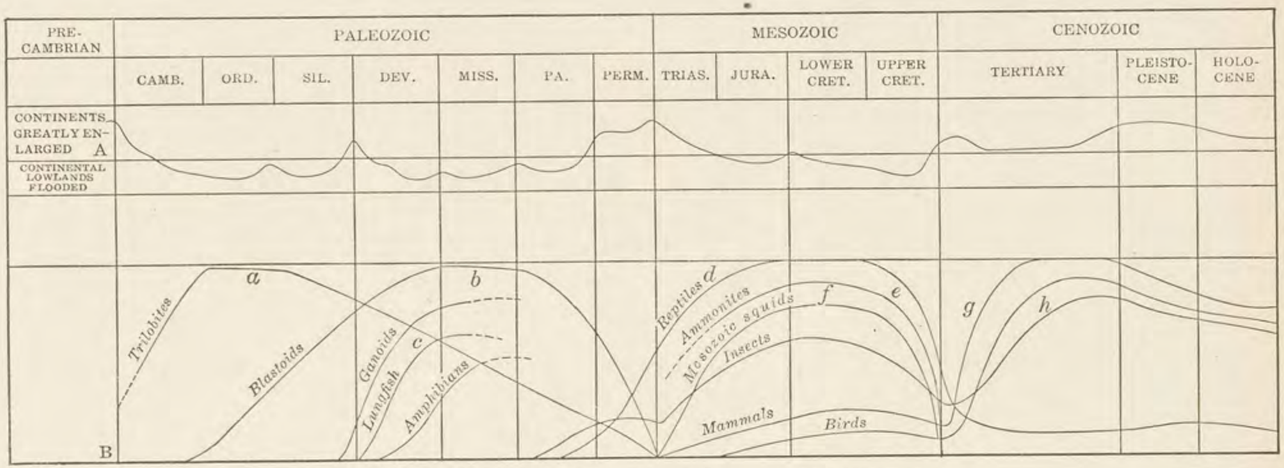
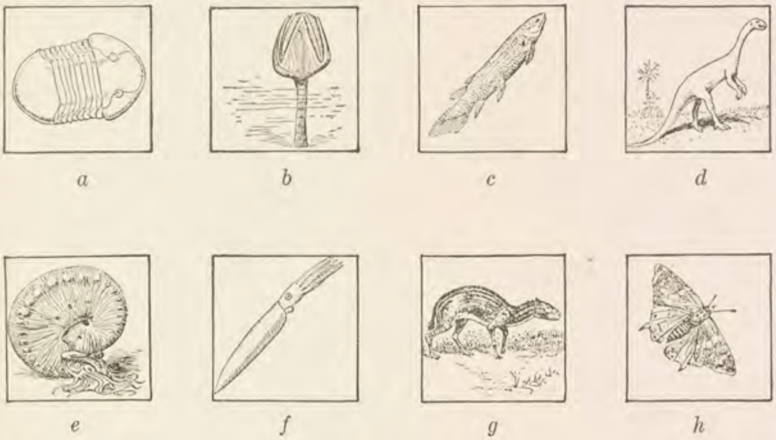


Fig. 139. Parallelism between earth waves and life waves

Accompanying exceptionally great physical changes in the surface of the earth old groups of plants and animals become extinct and new groups evolve. Only the most important of the mountain-making periods and the many incomings and withdrawals of the ocean waters are noted in the curves of A itself has undergone must likewise be traced; the environment in which the animals and plants lived must be determined — each successive change in the relation of land to sea, the distribution of glaciers and deserts, variations in moisture and in temperature. In brief, a continuous picture must be formed of the constantly though slowly changing physical conditions throughout the millions of years during which life has existed on earth. Only the broad outlines of this succession are known at present, but that is enough to give suggestions as to the stimuli given to the evolving plants and animals. This force, however, can affect only those organisms that are sufficiently evolved to respond to the stimulus. The spur of environment alone would not be sufficient to produce change. There must have been something within certain individuals capable of responding to this spur. Just as among men today some will


a *b* *c* *d*

e *f* *g* *h*

Fig. 140. Examples of typical life forms of successive eras to illustrate the life waves in Fig. 139

a, top view of the Ordovician trilobite *Isotelus gigas*, three inches long; *b*, side view of the Mississippian blastoid *Pentremites godoni*, two inches high; *c*, the Devonian lungfish Dipterus, eight inches long; *d*, the carnivorous dinosaur Anchisaurus, six feet long, from the Triassic; *e*, the ammonite Scaphites, three inches high, abundant in the Cretaceous seas of North America; *f*, the Mesozoic squid Belemnites, one foot long; *g*, the four-toed horse Eohippus, one foot high, of the Eocene of North America; *h*, the butterfly Prodryas, from the Miocene of Florissant, Colorado adapt themselves to radically changed conditions beneath which others go down, so with the lower organisms.

To illustrate the intimate relationship between the influence of changing environment and changes in plants and animals, three periods in earth history will be briefly summarized — late Silurian and early Devonian, late Paleozoic and early Mesozoic, late Mesozoic and early Cenozoic (Figs. 139, 140).

The late Silurian was characterized by a world-wide withdrawal of ocean waters from the lower-lying lands and by the development of huge mountains extending from Spitzbergen and Scotland to northern Africa, and from Ireland to Belgium. During the times of summer droughts a premium would naturally be placed upon those individuals that adapted themselves to the new conditions. The fish and certain plants were sufficiently evolved to respond to this demand. Hence we find that, accompanying these climatic conditions, there came into existence ganoids and lungfish, both having in addition to their gills a lung for getting oxygen when, during late summers, the stagnant pools became very impure. Similarly there came into existence at this time the ferns, horsetails, club mosses, and seed-ferns — plants that during part of the year could withstand dry conditions.

During the late Paleozoic and early Mesozoic occurred one of the most profound periods of physical change the world has known. Throughout the Pennsylvanian and early Permian, mountains were being upheaved, especially in Europe and eastern North America; in the early Permian there occurred one of the greatest glacial invasions the earth has experienced, and nearly all the known lands were both increased in height and extended beyond their present borders. Consequently the ocean waters, as well as the lands, underwent great physical changes, which extended into the early Mesozoic. During this time such large groups as the blastoids and trilobites disappeared from the ocean waters, the eurypterids from the fresh waters, and the giant rushes (calamites), tree club mosses, and seed-ferns from the lands. At the same time there came into existence reptiles, mammals, birds, and some higher insects.

During the late Mesozoic and early Cenozoic the continents and oceans were again profoundly affected. Such ranges as the Rockies and Andes were formed, and nearly all the present continents except southern Eurasia were uplifted and extended from their Cretaceous boundaries. This time saw the disappearance of the huge group of marine ammonites and the Mesozoic squids (belemnites), the aquatic classes of plesiosaurs, ichthyosaurs, and mosasaurs, the flying reptiles (pterosaurs), the land reptiles (dinosaurs), and the toothed birds. It saw the incoming of the more intelligent modern mammals and birds.

From external skeleton for protection to internal skeleton for support. As the life of the earth from the earliest times to the present is passed in review many lines of progressive modification may be noted. The following is illustrative. The earliest forms of animal life upon earth could not have been sufficiently complex to possess any skeleton. They were simple masses of protoplasm. As the ability to secrete a skeleton arose, emphasis in the struggle for existence was naturally placed upon the protective aspect, since no animals had as yet evolved a high degree of activity through which they might avoid enemies. Thus the earlier Paleozoic time is especially characterized by sluggish animals with an external protective skeleton. This was the time when the simpler invertebrates were dominant — the sponges, primitive hydroids, corals, bryozoans, brachiopods, and primitive mollusks and echinoderms. From the middle Paleozoic increasingly to the present the external skeleton of the more active animals has tended to become thinner, being utilized more for support than for pro-

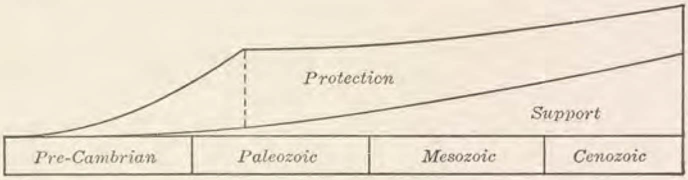


Fig. 141. Diagram to show the changing relation of the functions of protection and support in the development of the skeleton from the Archeozoic to the present

tection, as is seen in such highly developed arthropods as insects and spiders, or has been largely replaced by an internal skeleton, as in the most active and intelligent mollusks (the squids) and in the vertebrates. This change from an external skeleton, mainly for protection, to an internal skeleton, mainly for support, is an expression of the change from sluggishness to activity, from a low nervous organization to an increasingly higher mentality (Fig. 141).

An increasing control of both forces and their effects. The one-celled protozoöns are drifted ashore by waves and smothered by mud and sand. Their control over the forces of nature is exceedingly limited. Very slowly and gradually did later and higher forms of life acquire increasing control. From the more active and powerful jellyfish to the much better controlled and directed mollusk; from the fish, swift but confined to the water, to the reptile, at home in water or on land; and from such a mammal as the dog, fleet, intelligent, and indifferent to snow, rain, and wind, to man, who directs his movements toward more varied ends, an increasing independence of environment has been gained.

Notwithstanding his increased ability to reason and his tremendous growth in knowledge during the last three centuries, man is still greatly influenced by the earth on which he lives and by the natural forces encompassing him. The frigid zones, the larger deserts, and the summits of the high mountains have few inhabitants. The character of the earth's surface, shaped by causes acting millions of years ago, determines whether man may cultivate his food easily or not at all: the decay of basalts and of calcareous shales produces fertile soils; pure sandstones yield poor soils. The development of ores and of mountains determines where many men live today. Similarly, though man is overcoming many of the disadvantages of earth's topography by means of railroads, tunnels, and ship canals, still, to keep down the cost of transportation and thus make the products of his activity available to all, he makes use of the mountain passes, produced long ago by lessened uplift or erosion. For the same reason many of the large cities — New York, Philadelphia, Chicago — have developed at the head of waterways, thus obtaining cheap transportation. The proximity of iron ore and of the large quantities of coal necessary for smelting it—a proximity established millions of years ago—determines the importance of the Ruhr District in Germany and of Birmingham, Alabama, as well as the location of the plants of the United States Steel Corporation in Indiana and western Pennsylvania. The presence of waterfalls, brought into existence by the deflection of drainage due to the Pleistocene glaciers, established the conditions necessary for water-power manufacturing in northeastern United States and Canada and in northwestern Europe, just as the development of coal beds during the Carboniferous times in central and western Europe and central and eastern United States determined the location of other manufacturing centers. Similarly, the deposition of porous rocks and the elevation of their edges into mountain heights, which occurred ages ago, gives an artesian water supply to such regions as Kansas and Nebraska (pp. 226, 227).

While all life is thus dependent upon physical conditions,—the product of a sequence of cause and effect operating through millions of years,— man is the only creature that can modify these conditions to any degree. He alone of all organisms may greatly utilize nature's forces and their effects, the number that he uses depending upon his knowledge of them and his ability to guide and control them to desired ends.

TOPICAL REVIEW

The progressive variation of life
Physical changes at the earth's surface produce changes in life
From external skeleton for protection to internal skeleton for support
An increasing control of both forces and their effects

APPENDIX

The spectroscope and its uses. Every atom in every substance is in continuous motion. These movements set up wave movements in the ether at rates varying according to the number of vibrations of the atom. All ether waves travel at the rate of 186,000 miles a second; it is the number of waves sent out each second by the atom that varies, making the waves shorter (that is, closer together) or longer (that is, farther apart). When the waves come within a certain range of length, they may be apprehended by our eyes, which are mechanisms adapted to the perception of ether waves of such length. The effect which these waves produce upon our retinas, optic nerves, and brain is called light and color.

The spectroscope is an instrument which separates the waves according to their length by means of a prism and a slit. The prism separates the ether waves between infra-red and ultra-violet (that is, those waves which produce the sensation of light to our eyes) by bending them as they pass through it. The shorter the wave the more it will be bent, and thus the waves arrange themselves in the order of their wave lengths, from the shortest, which give us the sensation of violet (64,000 to an inch) through indigo, blue, green, yellow, and orange to red, the longest (34,000 waves to the inch).

The continuous spectrum. If a wire is heated to redness, the spectroscope shows the red end of the spectrum only. If now this is gradually raised to white heat, the yellow and bluish-white rays will in turn appear. Gaslight is redder than the electric arc because it is not so hot, and consequently its waves are longer. The hotter the substance, the farther does its spectrum stretch into the violet and ultra-violet region.

Bright-line spectra. Only in solids, liquids, and some dense gases are the atoms so lacking in freedom of movement that, being crowded together, the waves which they send out follow one another in a continuous series and thus produce a continuous spectrum, that is, an uninterrupted band of light, red at one end and violet at the other. In all substances that vaporize, the molecules are free to move at their own peculiar rate, during the vapor stage, and hence each sends out ether waves of its own particular length, resulting in its peculiar color. When common salt (NaCl) is dropped into a candle flame, the flame becomes yellow and the spectrum is seen to be made up of only two prominent yellow lines. There are a limited number of bright lines (that is, a definite bright-line spectrum) for each substance that vaporizes or is normally a gas. Sodium has 2 lines, calcium 75, iron over 2000, and each of these has a definite position in the spectrum.

Dark-line spectra. If, however, a stronger white light (that is, one giving all wave lengths) is placed back of the candle so that it shines through the candle flame, and salt is again shaken upon the candle flame so that the gas of NaCl is produced, the place of the two prominent bright yellow lines of sodium is taken by two prominent darker, though not black, lines. In other words, vapors and gases, when relatively cool, absorb those rays which they themselves give forth when incandescent, for the weaker waves absorb much of the stronger.

It was early noted that the sun's spectrum has almost innumerable vacancies of color, that is, dark lines; these have been called, after their discoverer, Fraunhofer lines. Later it was found that these dark lines correspond in position to the bright lines of various vapors. Thus the physicist, through the analysis of the spectrum, can note the presence in other worlds of the elements that are found in this; similarly, if lines occur which he cannot recognize in any spectra on our earth, he knows that he is observing a new substance.

Speed and direction of motion of a star. A train coming toward us sounds with a higher pitch than one that is going from us, because the waves in the former case are crowded upon one another and hence are shortened. Similarly, when a star is going from us the waves of light from it are crowded toward the red end of the spectrum, and when coming toward us they are crowded toward the violet end; the amount of the crowding is proportionate to the speed of the star. Thus the speed of movement of a star may be determined.

The gaseous hypothesis of Laplace. This hypothesis in its original form has probably no adherents today, though it has been most fruitful in the impetus it has given to investigation. In 1798 Laplace published a large volume on general astronomy, at the end of which was a short note on the origin of the solar system; this explanation was at once widely accepted. In brief, this hypothesis holds that our solar system evolved from a hot gaseous nebula which extended beyond our farthest present planet. This nebula had a slow rotation which increased through loss of heat and consequent contraction in size. In time an outer ring of nebulous material came into equilibrium under the centrifugal and gravitational forces, and, refusing to be drawn farther toward the center, was left behind, rotating as a solid. This process was repeated for other rings until only the sun was left at the center. The nebulous material in each ring gradually drew together into a still gaseous spheroid, which, again contracting, left behind one or more rings; these rings condensed into moons, while the contracting centers became the planets. The rings nearest to Saturn were presumed to be such gaseous rings not yet formed into planets. The following are a few of the many objections that have been raised against this hypothesis:

1. The nebular material before contraction must have been several hundred million times less dense than the air we breathe. The successive abandonment of rings, each rotating as a solid structure, is unthinkable.

2. If planetary rings were abandoned by centrifugal action, the sun should rotate in the plane common to that of the revolution of the planets; in reality its equator is inclined at an angle of 7 degrees to this plane.

3. If Mercury was abandoned as a ring, the speed of axial revolution at the sun's equator at this time must have been 28 miles (45 km.) a second (the speed of Mercury in its orbit). If the sun has since contracted to its present size, its equatorial velocity should now be 250 miles (400 km.) a second, in accordance with the law of constancy of moment of momentum. The sun's speed is actually 1.2 miles (2 km.) per second (Campbell).

The solar cyclonic hypothesis of origin of glacial periods. Times of increase in the number of sun spots seem to be correlated with times of increase in tidal pull and accompanying electrical disturbances of the giant planet Jupiter when it is nearest the sun. Jupiter's period of revolution is 11.86 years. The period of maximum sun-spot activity is 11.2 years (the 11-year cycle), the variation from Jupiter's period being probably due to the varying conjunctions of the other planets. When the sun spots are more numerous, the sun sends more heat to the earth. Since most of the increased heat would be received within the tropics, the ascending air column would be wider and stronger, with consequent broader trade-wind belts and desert belts on its polar sides. Consequently the rainy belt of westerlies would be pushed farther poleward. Thus today, when in the 11-year cycle the sun spots become more numerous, the rainfall is increased in central and eastern Canada and in northwestern Europe, the areas covered by the great ice sheets of the Pleistocene.

The increased heat received by the earth during times of increased sun spots causes the air to move more rapidly and hence take more heat from the surface of the earth to higher levels and thus make the earth colder. Between the times of maximum and minimum sun spots today there is a difference of 3° C. in earth temperature (Huntington). The years 1906 and 1917 were years of sun-spot maxima.

In Labrador today, when the summers are cool or exceptionally cloudy the snow persists the year round (Cabot). Hence a very slight decrease in temperature in this area and a slight increase in rainfall would give rise to small glaciers today. If now the rainy belt of the Great Lakes and New England were pushed northward to Hudson Bay and Labrador, and if this were accompanied by a reduction of from 9 to 11 degrees of temperature, there would (according to many meteorologists) be a return of the great Pleistocene ice sheets.

Such a change, however, would require a greater degree of storminess than is produced by the normal 11-year cycle of sun spots, and if the cause of glacial periods is to be sought in an increase or decrease of solar heat, apparently we must look to the nearer stars for some additional disturbing element. Of these, Alpha Centauri, a triple, bright, and rapidly moving star, is today the nearest of all. When, in swinging around their orbits, our sun and this star (or any one of many others) approach nearest each other, it might be near enough to cause sufficient disturbance in our sun to produce the requisite amount of storminess on earth. This is the least known part of this hypothesis.

Thus, without any change except a slight decrease in temperature and the northward movement of the rainy belt in North America and Europe, ice fields would again be formed in central Canada and in northwestern Europe.

Just as the land absorbs more heat than water does, causing the colder air from the ocean to crowd under the warm air, thus giving rise to the typical afternoon and evening sea breezes of our coasts, so the interiors of vast snow fields are always areas of high pressure, with the winds blowing outward. In the interior of Greenland and

Antarctica there is but little precipitation. At the south pole there is only a slight rise inland over the ice — 3000 feet in 1200 miles, according to Shackleton — and the mountains project through the ice even near the pole. Thus, in the case of the Pleistocene Labrador ice sheet, with outward-blowing cold winds, and with the rainy belt (the cyclonic lows of our westerlies) crowding north against the southern side of the developing ice sheet, there would occur great precipitation, with a consequent southward progression of the ice field. Hence the permanent ice fields would move southward without the necessity for a huge increase in the thickness of the ice in the central part of the field, which apparently does not exist in either Greenland or Antarctica.

The late glacial period was not one single period, but a composite of four or five distinct glacial advances separated by warm interglacial epochs. These intervals, from one glacial epoch to another, appear to form a declining series, 16–8–4–2–1 (Chamberlin and Salisbury). In this series unity is the time from the climax of the last (Wisconsin) glacial epoch to the present (that is, some 20,000 years). As an accessory cause of this alternation the precession of the equinoxes (Croll's eccentricity hypothesis) has been appealed to. At present the earth is 93,000,000 miles from the sun in January; in July it is 97,000,000 miles distant. But since the earth's axis precesses like a spinning top, there is a steady change in the season at which the earth is nearest the sun. In 21,000 years it varies from early in January through the twelve months back to January; that is, the Northern Hemisphere would naturally receive more heat when the north pole was tipped toward the sun in July when 93,000,000 miles distant than it does today when 97,000,000 miles away. Still another factor enters to vary this period of 21,000 years. In about each hundred thousand years the planets become bunched, and hence all pull in one direction, so that the earth's orbit becomes more elliptical, and hence the amount of heat received from the sun would vary further. Apparently these two factors could not in themselves have caused the alternations in the late glacial period, though they may have aided considerably.

Seasons throughout earth history. If the axis of the earth's rotation has always had its present inclination of 23.5 degrees to the plane of its orbit about the sun (and there appears to be no definite proof that it has not), there must always have resulted the north-and-south movement of the wet and dry belts of the tropical and subtropical regions, producing an alternation of wet and dry seasons.

Similarly, in the polar regions there must always have occurred an annual alternation of continuous sunshine with its total absence; this alternation, unless some other cause contravened, would give the alternation of summer and winter now characteristic of the temperate and polar regions.

The presence of thin and very regularly spaced banding in slates, shales, and shaly sandstones appears to be best interpreted as due to an alternation of wet and dry seasons. Such rocks are found in the strata of most geologic periods.

Growth rings in trees may be interpreted as due to an alternation of either wet and dry or warm and cold seasons. Both drought and cold retard or stop the growth of cells, while the opposite conditions accelerate it, thus producing a ring of newly grown wood cells. Growth rings have characterized vegetation since the Devonian, when for the first time in the history of the earth plants became sufficiently evolved to show such response to climatic variations. In the Devonian (Genesee) of New York (43° N.) the coniferlike Cordaites show growth rings. They have been found in the same genus in the Pennsylvanian of Oklahoma (36° N.), of Pennsylvania (41° N.), and of many other localities farther north, both in North America and in Europe (Goldring). Growth rings are common in the Permian of France (47° N.), in the Triassic Fossil Forest of Arizona (35° N.), etc. Since growth rings throughout geological history appear to be more abundant toward the poles, most of them may apparently be interpreted as due to an alternation of warm and cold seasons. Three other factors which appear to point to the same conclusion are as follows: (1) Throughout geological history the great limestone deposits, which today are forming most abundantly in warm waters, thin poleward. (2) Evidences of the former presence of glaciers are much more numerous throughout earth history in temperate and polar regions than within the tropics. (3) Throughout the history of the earth warmth-loving plants and animals decrease northward. The large, thick-shelled, water-dwelling animals are very rarely found in the colder temperate or polar regions, but they are common elsewhere. Even during the Cretaceous, when widespread seas give evidence of a warmer climate over all the earth, the foraminiferal protozoöns, sponges, corals, and peculiar bivalved rudistids disappear poleward (Schuchert).

From such lines of inquiry there is evidence that wet and dry seasons have characterized the surface of the earth from early geological times to the present, and that warm and cold seasons have been present at least very frequently throughout its past history. There is much evidence, however, that there occurred at intervals periods of apparently universal warmth, when warm temperate and even subtropical plants and animals lived freely within the Arctic and Antarctic circles.

Apparently, then, some cause entered at times to neutralize the well-known effects of the annual presence and absence of sunshine in the polar regions. Of the various hypotheses advanced to account for these, two will be cited.

T. C. Chamberlin has postulated a reversal of the deep-seated oceanic circulation. The present direction of this deep circulation is due to the balance between the waters of the polar regions, rendered heavy by cold, and the waters of the tropics, rendered heavy by a concentration of the salts from the great amount of evaporation. Today, on account of the huge quantities of cold fresh water supplied from the melting of the polar glaciers, a greater part of the polar waters, being heavier than the surface waters of the tropics, sinks to the bottom of the ocean basins, and, flowing thence to the tropics, rises. If, however, these glacial waters should be greatly lessened (and the glaciers are today retreating), the surface waters of the tropical regions might overbalance them and, sinking, flow as a bottom current to the poles. Rising there, they would produce a heavy fog, continuous at least during the polar nights, beneath whose protecting surface there would be a constant supply of tropical heat.

According to the solar cyclonic hypothesis of Huntington (see page 395) a similar result would be attained in a postulated increase in the flow of the present surface ocean currents. According to this hypothesis a reduction in the number of sun spots below that of today would be accompanied by a reduction in the number and strength of cyclonic storms. This reduction would give to the trade winds, to the southwesterly winds of the Northern Hemisphere, and to the northwesterly winds of the Southern Hemisphere a more continuous movement in one direction, for they would be less frequently blown out of their course by cyclonic storms. Thus the poleward-flowing tropical currents would flow more steadily and farther, and hence would probably promote a warm climate even within polar lands.

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