

McGraw-Hill Encyclopedia of the

# Geological Sciences



# **McGraw-Hill Encyclopedia of the Geological Sciences**

**Daniel N. Lapedes**  
*Editor in Chief*

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# Preface

Public interest in the Earth until recently has been transitory, being limited to natural disasters such as earthquakes and erupting volcanoes. However, the environmental movement of the 1960s and the energy problems of the 1970s have changed that attitude considerably. As a result, there has been a great increase in people's awareness of the fragility of the earth system and of the finite limit of its nonrenewable natural resources.

We who live on planet Earth have come to realize that this platform spinning through space is still undergoing fundamental change. Although the Earth with its present mass and density is approximately 4.6 billion years old, many of the mechanisms that produced the features we see are still operating at an undiminished pace. One of the most exciting ideas in the geological sciences today is plate tectonics, which theorizes that the surface of the Earth is broken up into a series of plates which move with respect to each other. Interactions between the plates at their boundaries are responsible for earthquakes, volcanism, and mountain building. A logical extension of plate tectonics is the theory of continental drift. The most recent episode of such drift has given the continents their present form and distribution.

Scientists studying the Earth as a whole consider it to be a dynamic system with solid, liquid, and gaseous phases. These are known to us as the solid earth, the oceans, and the atmosphere. The dynamics of this system have been of interest mainly to the geological scientist, oceanographer, and meteorologist.

The geological scientist is interested in the solid earth and may follow that interest in the areas of geology, geophysics, or geochemistry. Geology is the study of the nature of earth materials and processes and how they have interacted through time to leave a record of past events in existing earth features and materials. Geochemistry is the study of the earth system and the way matter has interacted in the system through time. Geophysics deals with the physical characteristics and dynamic behavior of the earth system and thus concerns itself with the diversity of complex problems involving natural phenomena.

While the primary interest of the geological scientist is the solid earth, that interest is not isolated from considering the effects of the oceans and the atmosphere upon the Earth. This encyclopedia provides a comprehensive treatment of the geological sciences, including geology, geochemistry, geophysics, and those aspects of oceanography and meteorology which are essential to understanding the materials, processes, composition, and physical characteristics of the solid part of the Earth.

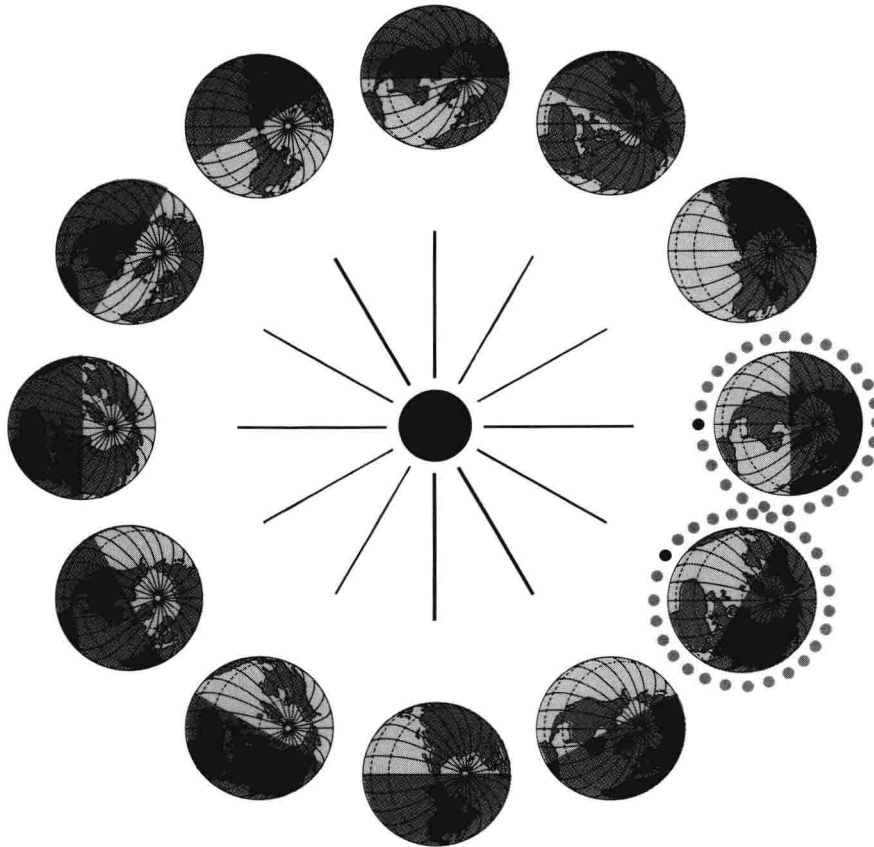
The articles included in the Encyclopedia were selected by a Board of Consulting Editors and either have been taken from the *McGraw-Hill Encyclopedia of Science and Technology* (4th ed., 1977) or have been written especially for this volume. The broad scope of geological sciences is covered in great depth in the 560 alphabetically arranged articles on subjects such as plate tectonics, oceans, geological time scale, paleontology, mineralogy, physiographic provinces, orogeny, high-pressure phenomena, geophysical explorations, geochemistry, and atmospheric chemistry.

The volume contains over 700 photographs, maps, tables, drawings, graphs, and diagrams. Cross-references appear within each article to guide the reader to articles on related subjects. All information in the Encyclopedia is easily accessible through an extensive analytical index. An additional useful feature is a table in the Appendix which lists the properties of 1500 mineral species.

DANIEL N. LAPEDES  
EDITOR IN CHIEF

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# A Z

## Aeolian (desert) landforms

Topographic features generated by the wind. The most commonly seen aeolian landforms are sand dunes created by transportation and accumulation of windblown sand. Blankets of wind-deposited loess, consisting of fine-grained silt, are less obvious than dunes, but cover extensive areas in some parts of the world.

**Movement of particles by wind.** Although wind is not capable of moving large particles, it can transport large amounts of sand, silt, and clay, especially in desert or coastal areas where loose sand and finer particles are exposed at the surface as a result of the scarcity of vegetation or the continuous supply of loose material.

The size of particles which can be moved by wind depends primarily on wind velocity. Swirls and eddies associated with wind turbulence have upward components of movement which pick up loose material. The velocity of upward gusts is usually not very constant, but generally averages about 20% of mean wind velocity. Where turbulence is strong enough to overcome the force of gravity, the particles remain suspended in the air

and are carried downwind. Because the maximum size of a particle suspended in the air varies with the square of its radius, wind is generally limited to the movement of material of sand size or smaller, and suspended particles are quite sensitive to changes in wind velocity. Thus, the wind is an effective winnowing agent, separating finer from coarser material, and grain size of aeolian deposits is typically quite uniform.

Windblown sand seldom rises more than a few feet above the ground. However, fine silt and dust may rise to altitudes of hundreds or thousands of feet during desert windstorms. Individual sand grains rise and fall as they are blown downwind and travel in a bouncing fashion known as saltation. Sand grains bouncing along the ground within a few feet of the surface abrade materials with which they collide. Such natural sand blasting produces polished, pitted, grooved, and faceted rocks known as ventifacts, and mutual abrasion of the sand results in highly rounded, spherical grains.

Silt- and clay-sized particles can be held in suspension much longer than sand grains, and thus may travel long distances before settling out.





Fig. 1. Barchan dunes at Moses Lake in Washington.

**Sand dunes.** Where abundant loose sand is available for the wind to carry, sand dunes develop. As soon as enough sand accumulates in one place, it interferes with the movement of air and a wind shadow is produced which contributes to the shaping of the pile of sand. Sand grains bounce up the windward side of the sand pile until they reach the crest, then tumble down the lee side in the wind shadow behind the crest. Sand trapped in the wind shadow accumulates until the slope reaches the angle of repose for loose sand, where any additional increase in slope causes sliding of the sand and development of a slip face. Dunes advance downwind by erosion of sand on the windward side

and redeposition on the slip face. Dunes may have a variety of shapes, depending on wind conditions, vegetation, and sand supply.

**Barchan dunes.** These are crescent-shaped forms in which the ends of the crescent point downwind and the steep slip face of the dune is concave downwind (Fig. 1). The crescent shape is maintained as the dune advances downwind because the rate of movement of sand is somewhat slower in the central part of the crescent where dune height is greatest. Barchans are commonly found on barren desert floors, where they may occur singly or in clusters.

**Parabolic dunes.** Parabolic dunes also have crescent-shaped forms, except that the crescent faces the opposite direction and the steep slip face is on the convex rather than the concave side of the dune. They typically occur where vegetation impedes the advance of the points of the crescent, allowing the higher vegetation-free central part of the dune to move at a faster rate, leaving the ends of the dune trailing behind.

**Transverse dunes.** These are elongate forms whose long axes are at right angles to the prevailing wind direction. They frequently develop as a result of coalescence of other dune types.

**Longitudinal dunes.** These consist of long ridges parallel to the prevailing wind direction, often found where sand is blown through a gap in a high ridge. However, very large elongate dunes up to 700 ft (210 m) high and 50 mi (80 km) long also occur in regular rows in the desert regions of Africa and the Middle East.

**Star-shaped dunes.** Dunes of this type are found in some areas where the direction of prevailing winds shifts from season to season, piling up sand in forms with long radial arms extending from a central high point (Fig. 2).

**Fine-grained deposits.** The fine silt and clay winnowed out from coarser sand is often blown longer distances before coming to rest as a blanket of loess mantling the preexisting topography. Thick deposits of loess are most often found in regions downwind from glacial outwash plains or alluvial valleys such as the Mississippi Valley, southeastern Washington, and portions of Europe, China, and the Soviet Union. See LOESS; SAND.

[DON J. EASTERBROOK]

**Bibliography:** R. A. Bagnold, *The Physics of Blown Sand and Desert Dunes*, 1941; W. S. Cooper, *Coastal Sand Dunes of Oregon and Washington*, Geol. Soc. Amer. Mem. 72, 1958; D. J. Easterbrook, *Principles of Geomorphology*, pp. 288–303, 1969.

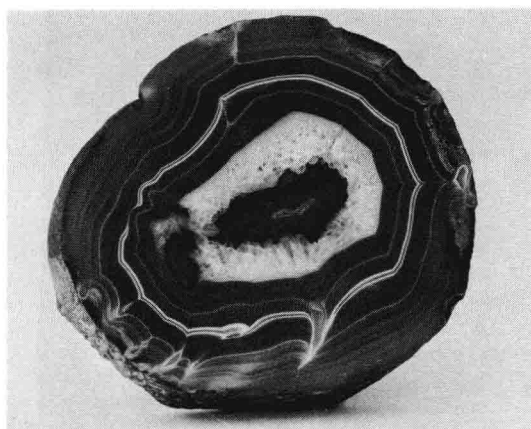
## Agate

A variety of chalcedonic quartz that is distinguished by color banding in curved or irregular patterns (see illustration). Most agate used for ornamental purposes is composed of two or more tones or intensities of brownish-red, often interlayered with white, but is also commonly composed of various shades of gray and white. Since agate is relatively porous, it can be dyed permanently in red, green, blue, and a variety of other colors. The difference in porosity of the adjacent layers permits the dye to penetrate unevenly and preserves marked differences in appearance between layers.

The term agate is also used with prefixes to de-



Fig. 2. Star-shaped dune at Death Valley in California.



Section of polished agate showing the characteristic color banding. (Field Museum of Natural History, Chicago)

scribe certain types of chalcedony in which banding is not evident. Moss agate is a milky or almost transparent chalcedony which contains dark inclusions in a dendritic pattern. Iris agate exhibits an iridescent color effect. Fortification, or landscape, agate is translucent and contains inclusions that give it an appearance reminiscent of familiar natural scenes. Banded agate is distinguished from onyx by the fact that its banding is curved or irregular, in contrast to the straight, parallel layers of onyx. The properties of agate are those of chalcedony: refractive indices of 1.535 and 1.539, a hardness of 6 1/2 to 7, and a specific gravity of about 2.60. See CHALCEDONY; GEM; QUARTZ.

[RICHARD T. LIDDICOAT, JR.]

### Albertite

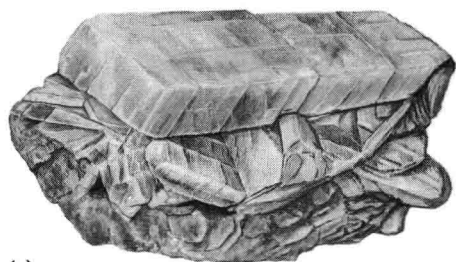
A naturally occurring, brown to black, carbonaceous substance associated with oil shales. It has a specific gravity of 1.07–1.10, is infusible, insoluble in carbon disulfide, and consists of approximately 79–89% carbon, 7–13% hydrogen, 0–5% sulfur, some oxygen, and traces of nitrogen. The material derives its name from the Albert Mines, Albert County, New Brunswick, Canada, where veins up to 17 ft wide have been traced for over 1/2 mi. Albertite also occurs in Pictou County, Nova Scotia; Uinta County, Utah; the Falkland Islands; Germany; Tasmania; and Portuguese West Africa.

Albertite is classified on the basis of its physical properties. Different deposits may have had variable contributions from different sources. Low oxygen contents of various samples of albertite indicate, however, that the material is not derived from coal in spite of its occasional occurrence near coal seams.

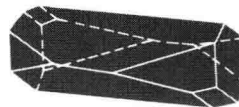
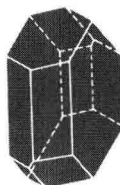
Albertite was mined for many years in New Brunswick and Nova Scotia for use in enriching bituminous coal in the manufacture of illuminating gas. See ASPHALT AND ASPHALTITE; ELATERITE; IMPSONITE; WURTZILITE. [IRVING A. BREGER]

### Albite

A sodium feldspar,  $\text{NaAlSi}_3\text{O}_8$ , with an Al-Si distribution producing triclinic symmetry (see illustration). Albite is usually found in nature with the highest state of Al-Si order which appears to be



(a)



(b)

Albite. (a) Crystals, Amelia Court House, Va. (specimen from Department of Geology, Bryn Mawr College). (b) Crystal habits (from C. S. Hurlbut, Jr., *Dana's Manual of Mineralogy*, 17th ed., copyright © 1959 by John Wiley & Sons, Inc.; reprinted by permission)

possible at low temperature. As a result of other Al-Si distributions of a less ordered character, several other states of  $\text{NaAlSi}_3\text{O}_8$  exist; for example, monalbite with monoclinic symmetry is stable under equilibrium conditions at temperatures ( $\approx 1000^\circ\text{C}$ ) near the melting point. Monalbite inverts upon cooling under nonequilibrium conditions into analbite that, like albite, is triclinic but has a somewhat different lattice geometry. The transformation temperature depends upon the degree of Al-Si disorder and the amount of  $\text{KAlSi}_3\text{O}_8$  or  $\text{CaAl}_2\text{Si}_2\text{O}_8$  present. Albite in its most ordered form cannot take more than about 2 mole % of  $\text{KAlSi}_3\text{O}_8$  or  $\text{CaAl}_2\text{Si}_2\text{O}_8$  as solid solution in its structure. See FELDSPAR; IGNEOUS ROCKS.

[FRITZ H. LAVES]

### Allanite

A mineral, also known as orthite, distinguished from other members of the epidote group of silicates by a relatively high content of rare earths, chiefly cerium, lanthanum, and yttrium. The chemical composition is  $(\text{Ca}, \text{Ce}, \text{La}, \text{Y})_2(\text{Al}, \text{Fe})_3\text{Si}_3\text{O}_{12}(\text{OH})$ . Other lanthanide elements are generally present, as is Be in some varieties. Small amounts of thorium and uranium are often present, and the mineral then may be metamict. Allan-



1 in.

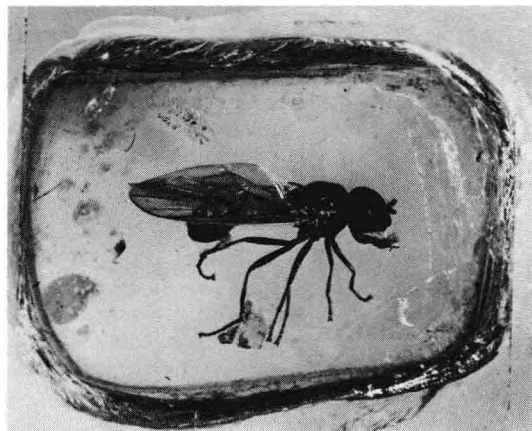
Allanite from Goiaz, Brazil. (Specimen courtesy of Department of Geology, Bryn Mawr College)

ite is monoclinic in crystallization. The color is black or brownish-black, and the specific gravity ranges from 3.4 to 4.2 (see illustration). Allanite is widespread as an accessory constituent in acid to intermediate igneous rocks and in gneissic metamorphic rocks. It is typical pegmatite mineral. See EPIDOTE; METAMICT STATE; RADIOACTIVE MINERALS.

[CLIFFORD FRONDEL]

## Amber

A fossil resin derived from a coniferous tree. It has been used for ornamental purposes since prehistoric times, for it is mentioned among the first recorded references to beads and other ornamental objects. When used for jewelry purposes, it is usually a transparent yellow, orange, or reddish-brown color. It frequently contains insects that were entrapped when the resinous tree exudation was still in a semiliquid state (see illustration). Amber of a translucent or semitranslucent type is used for decorating small boxes, for pipe stems, and for a variety of ornamental purposes.



*Pseudosphagina carpenteri* Hull (Diptera), syrphid fly in Baltic amber, Oligocene. (Courtesy of F. M. Carpenter)

For centuries, the most important source of amber has been along the south shore of the Baltic Sea, particularly in the section of Poland that was Germany before World War II (East Prussia). Other sources are Burma, Sicily, and Rumania. There are only minor differences in composition and properties of material from the various sources. Amber is amorphous, has a refractive index of about 1.54, a specific gravity of 1.05–1.10, and a hardness of 2–2.5 on Mohs scale. In polarized light, irregular interference colors are exhibited as a result of pronounced internal strain. See GEM; MINERALOGY.

[RICHARD T. LIDDICOAT, JR.]

## Amblygonite

A mineral consisting of lithium, sodium, and aluminum phosphate ( $(\text{Li}, \text{Na})\text{Al}(\text{PO}_4)(\text{F}, \text{OH})$ ). Lithium and sodium substitute for each other but generally Li is in excess of Na; F and OH also substitute mutually. These substitutions give rise to an amblygonite series of minerals. Amblygonite crystallizes in the triclinic system. Crystals are short and prismatic. Colors range from white through shades of gray, yellow, green, and brown.

Amblygonite, found at many places in the world, occurs mostly in granitic pegmatites. It is mined in the Black Hills of South Dakota, in southwestern Africa, and elsewhere for its lithium content.

[WAYNE R. LOWELL]

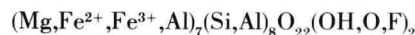
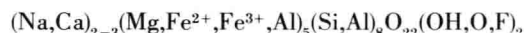
## Amethyst

The transparent purple to violet variety of the mineral quartz. Although quartz is perhaps the commonest gem mineral known, amethyst is rare in the deep colors that characterize fine quality. Amethyst is usually colored unevenly and is often heated slightly in an effort to distribute the color more evenly. Heating at higher temperatures usually changes it to yellow or brown (rarely green), and further heating removes all color. The principal sources are Brazil, Arizona, Uruguay, and the Soviet Union. Amethyst is often cut in step or brilliant shapes, and drilled or carved for beads. Carvings are made both from transparent and nontransparent material. See GEM; QUARTZ.

[RICHARD T. LIDDICOAT, JR.]

## Amphibole

A large group of common rock-forming inosilicate (metasilicate) minerals. The amphiboles exhibit a wide range of compositional variation, as indicated by the generalized formulas



The amphiboles represent a complex series of solid solutions between a variety of idealized end members. The species names of these end members are usually the best known; the more important ones are listed below. See SILICATE MINERALS.

### Orthorhombic amphiboles

Anthophyllite	$(\text{Mg}, \text{Fe}^{2+})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$
Gedrite	$(\text{Mg}, \text{Fe}^{2+})_5\text{Al}_2(\text{Si}_6\text{Al}_2)\text{O}_{22}(\text{OH})_2$

### Monoclinic amphiboles

Cummingtonite	$(\text{Fe}^{2+}, \text{Mg})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$
Tremolite	$\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$
Tschermakite	$\text{Ca}_2\text{Mg}_3\text{Al}_2(\text{Si}_6\text{Al}_2)\text{O}_{22}(\text{OH})_2$
Edenite	$\text{NaCa}_2\text{Mg}_5(\text{Si}_6\text{Al}_2)\text{O}_{22}(\text{OH})_2$
Glaucophane	$\text{Na}_2(\text{Mg}_3\text{Al}_3)\text{Si}_8\text{O}_{22}(\text{OH})_2$
Riebeckite	$\text{Na}_2(\text{Fe}^{2+}\text{Fe}^{3+})\text{Si}_8\text{O}_{22}(\text{OH})_2$
Arfvedsonite	$\text{Na}_3\text{Fe}_4^{2+}\text{Fe}^{3+}\text{Si}_8\text{O}_{22}(\text{OH})_2$
Eckermannite	$\text{Na}_4\text{Mg}_4(\text{Fe}^{3+}, \text{Al})\text{Si}_8\text{O}_{22}(\text{OH})_2$

**Composition.** Each of the listed calcium (Ca) amphiboles has a ferrous iron equivalent and would be indicated by the prefix ferro-, for example, ferrotremolite. Also, some ferric iron and oxygen in the place of the OH groups can occur in the ferroamphiboles and is indicated by the prefix ferri-, for example, ferritremolite; the term oxyhornblende is commonly applied to the ferriamphiboles. A high content of fluorine is indicated by the prefix fluoro-, for example, fluorocummingtonite. The iron content in the anthophyllite series seems to be limited to about 60 mole % of the iron end member; a higher concentration of iron results in the monoclinic cummingtonite. Cummingtonite with less than 25 mole % of the iron end member is unknown. The overlap, between 25–60 mole % iron, between the two series is probably the result



of different amounts of aluminum, particularly in the anthophyllite. For the Na-Ca amphiboles, solid solution between any of the end members is possible so that a single crystal could be composed of contributions from some 10 different end members. The general term hornblende is usually applied to these solid solutions of the Na-Ca amphiboles. Obviously, a chemical analysis is needed to determine the composition. However, certain physical features suggest the dominance of certain compositions. See ANTHOPHYLLITE; CUMMINGTONITE; HORNLENDE.

**Physical and optical properties.** All amphiboles are characterized by two directions of well-developed prismatic cleavages which intersect at approximately  $124^\circ$ . In detail, the magnesium-rich amphiboles are generally light colored (white, gray, light green) with the color darkening to dark green, dark brown, or black with increasing iron content. The presence of sodium is often indicated by a bluish color, especially in thin sections. The Mg-rich amphiboles commonly develop long needle-like or fibrous crystals, and there is a rough correlation such that, as the iron and aluminum content increases, the individual crystals become progressively more short and stubby.

**Occurrence.** The amphiboles as a group are present as minor constituents in many volcanic, igneous, and metamorphic rocks and are thus able to form over most of the temperature range observed in the Earth's crust. Amphiboles are present as major constituents in many metamorphic schists and gneisses, for example cummingtonite schist, glaucophane schist, and hornblende schist. These amphibole schists are most common in the middle grades of metamorphism. Amphiboles occur as gangue minerals in certain ore deposits and are found in many skarn deposits. Ferriamphiboles or oxyhornblendes are usually the product of oxidation of ordinary hornblendes in lava flows. Intertwined fibrous crystals of tremolite are known as nephrite and classed as one of the jades. Fibrous riebeckite is known as the semiprecious stone crocidolite or tiger's eye. Fibrous tremolite, anthophyllite, and riebeckite are used in commercial asbestos. Amphiboles can result from the alteration of pyroxenes. Amphiboles of this type are occasionally referred to as urallite and the process as uralization. The amphiboles can be altered to a variety of decomposition products with talc, antigorite, chlorite, and epidote the most commonly observed. See ASBESTOS; GLAUCOPHANE; JADE; TREMOLITE.

**Crystal structure.** The compositional variation is best explained from the viewpoint of crystal structure. In silicates four oxygens arranged at the corners of a tetrahedron surround each 4-valent silicon atom. These  $\text{SiO}_4$  tetrahedrons can share one, two, three, or four oxygen anions with one, two, three, or four neighboring tetrahedrons (one oxygen to each neighboring tetrahedron) and thereby reduce in steps the excess charges on the oxygen atoms. The amphiboles are characterized by the polymerization of the  $\text{SiO}_4$  tetrahedrons into endless double chains or ribbons. These double chains with the associated (OH,F,O) atoms are bonded to adjacent parallel double chains by the other metal atoms of the crystal. Extensive miscibility between atoms of similar size occupying essentially equivalent atomic sites (within charge

limitations) is very common in silicates. The ionic sizes of Mg,  $\text{Fe}^{2+}$ ,  $\text{Fe}^{3+}$ , and Al are similar enough that these atoms occupy the same type of atomic site in the mineral; Na and Ca occupy equivalent atomic sites, as do OH, O, and F. Limited substitution of the silicon atoms by aluminum atoms also can occur, which extends the range of compositional variation. Very commonly one-fourth of the silicon atoms are replaced by aluminum, but greater replacement than this by aluminum is rare. Solid solution between the cummingtonite series and the calcium amphibole series is not present even though the calcium sites can be completely replaced by the iron-magnesium atoms in cummingtonite.

**Genetic relations.** Because of the lack of solid solution between them, cummingtonite and the calcium amphiboles can exist together at equilibrium and they often occur intimately intergrown. Anthophyllite and cummingtonite can exist together, apparently at equilibrium, but anthophyllite coexisting with the calcium amphiboles seems to be rare.

The temperature of formation of the mineral assemblage is not particularly indicated by the amphiboles. However, the aluminum- and iron-rich hornblendes tend to occur in the higher grades of metamorphism and the aluminum-poor hornblendes in the lower grades of metamorphism. The sodium- and aluminum-rich hornblende hastingsite is often used as an index mineral for the highest grade of metamorphism (granulite facies).

[GEORGE W. DE VORE]

## Amphibolite

A class of metamorphic rocks. Amphibolites are crystalline schists (recrystallized, foliated metamorphic rocks) of greenish-black color composed of amphibole (hornblende) and plagioclase feldspar as essential minerals. Prisms of hornblende show a preferred orientation defining a lineation and, particularly if biotite is present, also a schistosity. Amphibolites are formed by regional metamorphism under the conditions of the amphibolite facies (about  $500^\circ\text{C}$ ). See METAMORPHIC ROCKS; SCHIST.

Among the metamorphic rocks, the amphibolites occupy a position similar to that of the basalt-gabbro rocks of the igneous suite. However, whereas basalts and gabbros have been extensively investigated, and well-known chemical and mineralogical criteria exist to distinguish the various types, such as tholeiites, tephrites, and basanites, no corresponding characterization has been made of amphibolites. A wide and virgin field is here open, and calculation of the newly proposed mesonorms will provide a means of standard comparison and thus serve as a convenient way of studying amphibolites chemically. A great number of chemical elements are able to enter into the crystal structure of hornblende [iron (II) for magnesium, sodium for calcium, iron (III) for aluminum, and others], whereby the number of constituent mineral phases in the rock is greatly reduced (the principle of the paucity of mineral phases). Thus amphibolites of very complicated chemical compositions are usually biminerally, containing just hornblende and plagioclase. Three or four chief minerals are not unusual, but to encounter five or six chief minerals is rare.

Amphibolites may be formed from rocks of rather diverse kinds, igneous and sedimentary. Frequently the nature of the original rock cannot be determined.

An igneous parentage (derived from gabbros, diabases, basalts, or basic tuffs) may reveal itself, for example, in weak foliation, but this is not a rule. Quartz and biotite are often present and in some rocks garnets may be present as conspicuously large, round porphyroblasts. The presence of epidote usually indicates a slightly lower temperature of formation. Minor amounts of sphene, apatite, and opaque ores are almost always present. Amphibolites derived from ultrabasic igneous rocks are very dark (black) with a high content of hornblende; biotite may be present, and sometimes anthophyllite. *See PORPHYROBLAST.*

Amphibolites of sedimentary parentage exhibit a much wider range of composition. The lime content especially is subject to large variations which are reflected in the mineral contents: diopside amphibolites, epidote (zoisite) amphibolites, and sphene may be abundant. In other types cordierite is present, often associated with anthophyllite.

Some amphibolites are truly metasomatic and may derive from impure limestone or dolomite which has reacted with "emanations" containing silica, magnesium, and iron.

Amphibolite has a wide distribution in areas of Precambrian rocks and in areas of deeply eroded younger mountain ranges. Next to granitic gneiss, amphibolite probably is the most abundant crystalline schist.

[T. F. W. BARTH]

## Amygdule

A mineral filling formed in vesicles (cavities) of lava flows. The lava rock containing amygdules is called an amygdaloid, or amygdaloidal lava.

Gases dissolved in liquid lava at depth come out of solution and form bubbles as the rising liquid reaches the surface of the earth. When the lava congeals to solid rock, the trapped bubbles are preserved as holes, or vesicles (see illustration). In pahoehoe lava the vesicles are rather regular spheroids or groups of coalescing spheroids—sometimes nearly spherical, but generally elongated and flattened because of flowage of the enclosing lava. The vesicles of aa and block lava are very irregular. *See VOLCANO.*

Amygdules may consist of mineral matter deposited by gases or liquids released during the

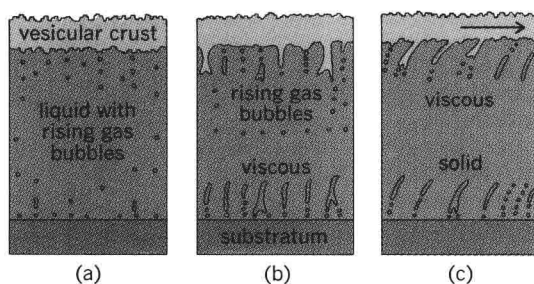


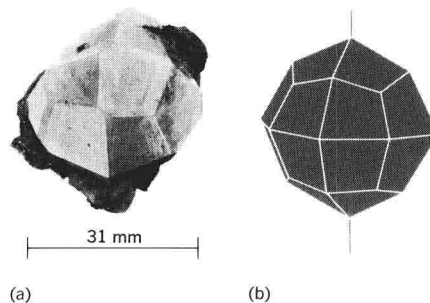
Diagram of spheroidal and pipe vesicles in lava flows. (a) Liquid flow with vesicular crust. (b) Congealing flow. (c) Nearly solidified flow. (From R. R. Shrock, *Sequence in Layered Rocks*, McGraw-Hill, 1948)

consolidation of the surrounding rock. Generally, however, they are deposited by fluids of extraneous origin moving through the rocks. The depositing agents may be hot gases and hydrous solutions rising in volcanic vent areas or in mineralized areas unrelated to volcanic vents; or they may be cold solutions in which the water is of meteoric (atmospheric) origin. The material deposited may be brought in from remote sources or derived by alteration of the adjacent rocks. The common minerals of amygdules are chalcedony, opal, calcite, chlorite, prehnite, pectolite, apophyllite, datolite, and various zeolites. More rarely, native copper and silver may be found. Well-formed amygdules of gibbsite are found, sometimes abundantly, in areas of lateritic alteration of basaltic lavas.

[GORDON A. MACDONALD]

## Analcime

A mineral belonging to the zeolite family of silicates, with composition  $\text{Na}(\text{AlSi}_3\text{O}_6) \cdot \text{H}_2\text{O}$ . It crystallizes in the isometric system and is usually found in trapezohedral crystals (see illustration).



Analcime. (a) Specimen from Keweenaw County, Mich. (*American Museum of Natural History*). (b) Trapezohedral crystal typical of analcime (from C. S. Hurlbut, Jr., *Dana's Manual of Mineralogy*, 17th ed., copyright © 1959 by John Wiley & Sons, Inc.; reprinted by permission)

The crystals are characterized by a complex internal structure composed of birefringent lamellae or sectors. Only rarely is it massive or granular. The hardness is 5–5 1/2 on Mohs scale; specific gravity is 2.27. Crystals are white or colorless with a vitreous luster. In color and crystal form analcime resembles leucite but can usually be distinguished from it by its free-growing crystals. Leucite is always embedded in a rock matrix. *See LEUCITE ROCK; ZEOLITE.*

Analcime is most commonly a secondary mineral found in veins and cavities of basic igneous rocks (usually basalts), where it is associated with other zeolites, datolite, prehnite, and calcite. Although rare, analcime has been found as a primary constituent of certain igneous rocks. It occurs in the copper deposits of Lake Superior and has been found in hydrothermal sulfide vein deposits. It also occurs as small bedded deposits in saline lakes in arid regions.

[CORNELIUS S. HURLBUT, JR.]

## Andalusite

A nesosilicate mineral, composition  $\text{Al}_2\text{SiO}_5$ , crystallizing in the orthorhombic system. It occurs commonly in large, nearly square prismatic crys-

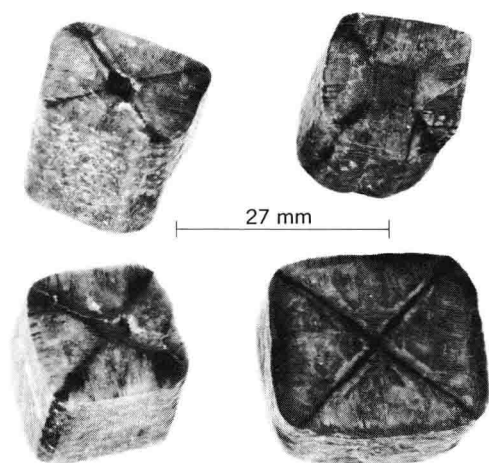


Fig. 1. Andalusite, variety chialtolite. Prismatic crystal specimens from Worchester County, Mass. (*American Museum of Natural History specimens*)

tals. The variety chialtolite has inclusions of dark-colored carbonaceous material arranged in a regular manner. When these crystals are cut at right angles to the  $c$  axis, the inclusions form a cruciform pattern (Fig. 1). There is poor prismatic cleavage; the luster is vitreous and the color red, reddish-brown, olive-green, or bluish. Transparent crystals may show strong dichroism, appearing red in one direction and green in another in transmitted light. The specific gravity is 3.1–3.2; hardness is 7 1/2 on Mohs scale, but may be less on the surface because of alteration. See SILICATE MINERALS.

**Occurrence and use.** Andalusite was first described in Andalusia, Spain, and was named after this locality. It is found abundantly in the White Mountains near Laws, Calif., where for many years it was mined for manufacture of spark plugs and other highly refractive porcelain. Chialtolite, in crystals largely altered to mica, is found in Lancaster and Sterling, Mass. Water-worn pebbles of gem quality are found at Minas Gerais, Brazil.

[CORNELIUS S. HURLBUT, JR.]

**Aluminosilicate phase relations.** The three polymorphic forms of  $\text{Al}_2\text{SiO}_5$  are andalusite (Fig. 1), kyanite, and sillimanite. These minerals occur in metamorphic rocks. Experimental determination of the stability fields of the three minerals, in terms

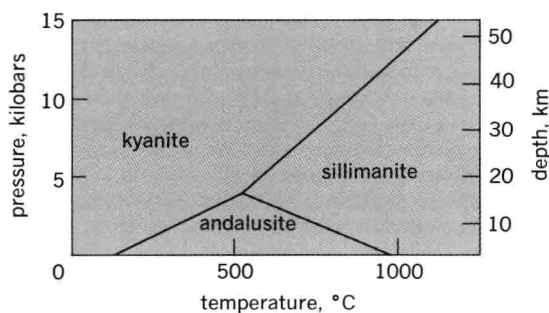


Fig. 2. Phase diagram for the polymorphs of  $\text{Al}_2\text{SiO}_5$ . (After R. C. Newton, *Kyanite-andalusite equilibrium from 700° to 800°C*, *Science*, 153:170–172, copyright 1966 by the American Association for the Advancement of Science)

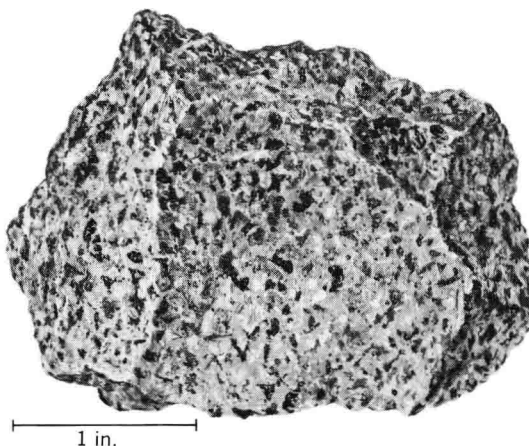
of pressure and temperature, has proved to be very difficult, but the phase diagram shown in Fig. 2 is a version now generally accepted; the experimental results are consistent with available thermochemical data. The three univariant reaction lines separating the stability fields of the minerals meet at an invariant point located near 4 kilobars pressure and 520°C.

The degree of metamorphism in rocks is indicated by index minerals. In many terranes of regional metamorphism, kyanite is succeeded by sillimanite, with increasing intensity of metamorphism. Figure 2 shows that for this sequence to develop the rocks must have been subjected to pressures greater than 4 kilobars, which corresponds to depths greater than 16 km in the Earth's crust. In other metamorphic terranes andalusite is developed on a regional scale, without kyanite or sillimanite, which indicates that the rocks were metamorphosed at higher levels in the Earth's crust. Thus, knowledge of the phase relationships of the polymorphic forms of  $\text{Al}_2\text{SiO}_5$ , combined with geological studies of rocks containing these minerals, is a useful aid in deducing the extent of vertical movements occurring in the Earth's crust. See KYANITE; SILLIMANITE.

[PETER J. WYLLIE]

## Andesine

A plagioclase feldspar with a composition ranging from  $\text{Ab}_{70}\text{An}_{30}$  to  $\text{Ab}_{50}\text{An}_{50}$ , where  $\text{Ab} = \text{NaAlSi}_3\text{O}_8$  and  $\text{An} = \text{CaAl}_2\text{Si}_2\text{O}_8$  (see illustration). In the high-temperature state, andesine has albite-type structure. In the course of cooling, natural material develops a peculiar structural state which, investigated by x-rays, shows reflections that indicate the beginning of an exsolution process, sometimes accompanied by a beautiful variously



Andesine grains with biotite, in a specimen from Zoutpansberg, Transvaal, South Africa. Andesine is rarely found except as grains in igneous rocks.

colored luster (labradorizing). If  $\text{Fe}_2\text{O}_3$  is present as thin flakes and oriented parallel to certain structurally defined planes, such andesine is called aventurine or sunstone. See FELDSPAR; GEM; IGNEOUS ROCKS.

[FRITZ H. LAVES]

## Andesite

A volcanic rock intermediate in composition and color between basalt and rhyolite and characterized by excess  $\text{SiO}_2$  (that is, presence of silica minerals in completely crystalline examples). Most andesite is porous tephra (tuff) erupted explosively from steep-sided volcanoes (Fig. 1). Many of the most explosive volcanic eruptions yielded andesite (Krakatoa, 1883; Sakurajima, 1914; and Bezymianyn, 1956). Such eruptions awe people by devastating wide areas, turning day into night, and reddening sunsets around the Earth for several years after the explosion. Powerful eruptions throw enough dust into the stratosphere to have a possible effect on the climate and even to influence the coming of ice ages.

Together with basalt, andesite is a principal volcanic rock of island arcs and continental margins. Andesite is generally rich in large crystals of plagioclase feldspar and has a partly glassy, finely crystalline groundmass. The average composition of andesite closely resembles that of continental crust. It appears likely that the formation of andesite and continental crust is a single complex response to the thrusting of oceanic lithosphere into the Earth.

**Definition.** Andesite is difficult to define because of usage which varied as techniques available to geologists changed from microscopic to analytical. The development of the meaning of the word reveals significant aspects of the rock type and of the interplay between words and understanding in sci-

entific progress. The rock is named for examples in the Andes Mountains, where widespread occurrences of the rock were first found, and dates to times (early 1800s) when igneous rocks were classified primarily according to their mineralogical makeup and grain size. Andesites proved difficult to identify owing to their fine grain size. Indeed, many andesites contain substantial proportions of glass. When chemical analyses became more readily available in the 20th century, rocks called andesite were found by F. Chayes in 1969 to have a broad range of compositions not intended by systematic schemes of classification. Since about 1960 andesite has been applied to rocks like those in the original region, that is, volcanic rocks of intermediate composition with an excess of  $\text{SiO}_2$ . Intermediate rocks deficient in  $\text{SiO}_2$  are called hawaiite and other names indicative of occurrence in oceanic regions, in contrast to andesites which are characteristic of mountainous continental margins and island arcs.

The distinction between andesite and basalt and dacite or rhyolite is variously defined according to proportions of light and dark minerals, composition of feldspar, or compositional relations between  $\text{SiO}_2$  and alkalies. Chayes noted that 1749 out of 1775 andesites have excess  $\text{SiO}_2$  and suggested that excess  $\text{SiO}_2$  be part of the definition of andesite. As basalts almost never have excess  $\text{SiO}_2$ , this is a natural dividing line between basalt and andesite. There is no comparable basis to distinguish between andesite and dacite, and most geologists term andesite all rocks with excess silica



Fig. 1. Two andesite volcanoes (Pavlof and Pavlof Sister, in front) in Alaska. (Photograph by Finley C. Bishop, 1974)



and more than about 10% of dark minerals (rhyolites have less).

**Structure, texture, and mineralogy.** Most andesite is erupted explosively and consists of porous fragments of tephra. Andesite tephra contains up to about 30 vol % of crystals larger than 1 mm set in a groundmass of tiny crystals and glass. The big crystals are generally well formed and dominated by plagioclase and pyroxene, both of which are commonly compositionally zoned. Big crystals of olivine and magnetite occur in many andesites; amphibole, biotite, and quartz are common only in the more siliceous andesites. The groundmass minerals are largely plagioclase with minor pyroxene, magnetite, and apatite. The groundmass glass is commonly rhyolitic in composition, but may be andesitic in rapidly cooled, glass-rich varieties. Crystals of cristobalite, tridymite, and hematite are common in the vesicles.

Flows and domes of andesite have craggy to blocky surfaces and platy, slabby, or massive interiors. The texture of flows and domes is similar to that of tephra, except that tephra is more porous and generally contains higher proportions of glass than do flows and domes. Some andesites rich in big crystals have bulk compositions outside the range found for andesites poor in big crystals.

**Composition, occurrence, and origin.** The chemical and mineralogical composition of andesite varies in space and time in a broadly regular way, but with many exceptions. Andesites on continental margins (such as the Alaskan peninsula) are more silicic, in general, than andesites on oceanic islands (such as the Aleutian Islands). Andesites near the ocean and above shallow zones of earthquakes tend to be poorer in alkalis and richer in lime than those farther inland associated with deeper seismicity. Volcanoes formed in the early stage of development of island arcs contain the most iron-rich andesites, except for analogs on truly oceanic islands.

Geological thinking during the 1970s is dominated by plate tectonic theory. Accordingly, the space-time variations of andesites are explained according to a hypothesis of partial melting of lithosphere in subduction zones. It appears unlikely that andesites are generated as such in subduction zones, although many scientists favor this possibility. In 1969 H. Kuno extended the hypothesis of N. Bowen that basaltic magmas feed volcanoes with andesite from large bodies of gabbroic magma near the base of the crust (Fig. 2). However, Kuno's hypothesis fails to give subduction an essential role in the origin of andesite. This was first done by R. Coats, in 1962, who proposed that water-rich sedimentary rocks were thrust deep into the Earth beneath island arcs and partially melted together with overlying mantle to yield basalt and related andesite. Geochemical studies showed that less than about 2% of the radiogenic lead and strontium in typical andesites could be derived from the kind of subducted rock proposed by Coats. C. B. Rayleigh and W. Lee proposed that the material of basalts and related andesites might be generated by partial melting of hydrous oceanic crust in subduction zones, and A. McBirney suggested that water derived from the subducted slab of dehydrating lithosphere would flux melting in the overlying mantle. The last two ideas can help explain some of the space-time variations of andes-

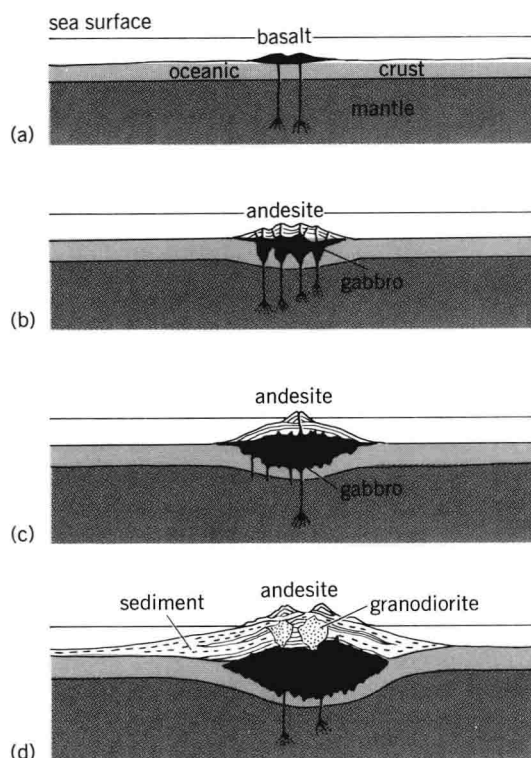


Fig. 2. Successive stages of development of island arc structure. (a) Initial formation of basaltic material on the sea floor in an island arc. (b) Development of reservoirs of gabbroic magma within the oceanic crust and submarine extrusion of andesite. (c) Coalescence of magma reservoirs, continued andesite extrusion, and crustal thickening adequate to support volcanoes above sea level. (d) Continued andesite extrusion from subaerial volcanoes and growth of silicic magma reservoirs (granodiorite) within the upper crust of volcanic and sedimentary materials, with further crust thickening. (From H. Kuno, *Origin of andesite and its bearing on the island arc structure*, *Bull. Volcanol.*, 37:141–176, 1968)

ites mentioned above: the nature of melting may change with progressive subduction, and water-fluxed melting of the overlying mantle may lead to variation in iron and alkalis with time and depth (extent) of dehydration of the subducted lithosphere. See BASALT; IGNEOUS ROCKS; OCEANIC ISLANDS; TECTONIC PATTERNS; VOLCANO.

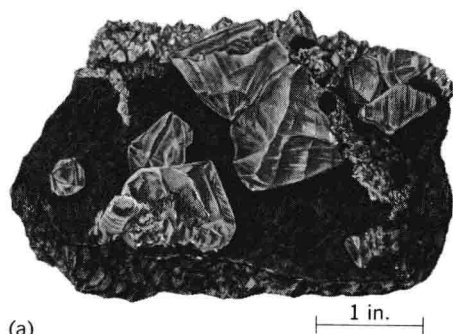
[ALFRED T. ANDERSON, JR.]

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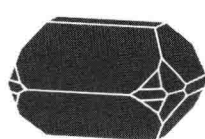
## Anglesite

A mineral with the chemical composition  $\text{PbSO}_4$ . Anglesite occurs in white or gray, orthorhombic, tabular or prismatic crystals or compact masses (see illustration). It is a common secondary mineral, usually formed by the oxidation of galena. Fracture is conchoidal and luster is adamantine. Hard-





(a)



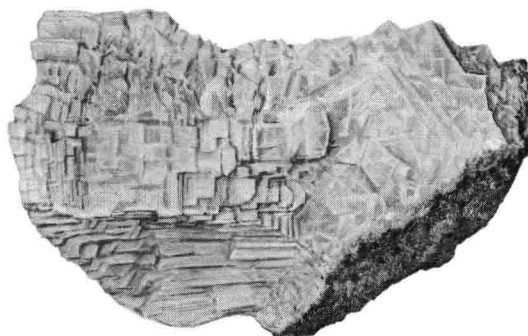
(b)

Anglesite. (a) Crystals on galena from Phoenixville, Pa. (Bryn Mawr College specimen). (b) Crystal habits (from L. G. Berry and B. Mason, *Mineralogy*, copyright © 1959 by W. H. Freeman and Co.)

ness is 2.5–3 on Mohs scale and specific gravity is 6.38. Anglesite fuses readily in a candle flame. It is soluble with difficulty in nitric acid. The mineral does not occur in large enough quantity to be mined as an ore of lead, and is therefore of no particular commercial value. Fine exceptional crystals of anglesite have been found throughout the world. In the United States good crystals of anglesite have been found at the Wheatley Mine, Phoenixville, Chester County, Pa., and in the Coeur d'Alene district of Shoshone County, Idaho. See GALENA. [EDWARD C. T. CHAO]

## Anhydrite

A mineral with the chemical composition  $\text{CaSO}_4$ . Anhydrite occurs commonly in white and grayish granular masses, rarely in large, orthorhombic crystals (see illustration). Fracture is uneven and luster is pearly to vitreous. Hardness is 3–3.5 on Mohs scale and specific gravity is 2.98. It fuses readily to a white enamel. It is soluble in acids and slightly soluble in water. Anhydrite is an important rock-forming mineral and occurs in association



Anhydrite from Montanzas, Cuba. (Specimen from Department of Geology, Bryn Mawr College)

with gypsum, limestone, dolomite, and salt beds. It is deposited directly by evaporation of sea water of high salinity at or above 42 °C. Anhydrite can be produced artificially by dehydration of gypsum at about 200°C. Under natural conditions anhydrite hydrates slowly, but readily, to gypsum. It is not used as widely as gypsum. Anhydrite is of world-wide distribution. Large deposits occur in the Carlsbad district, Eddy County, N.Mex., and in salt-dome areas in Texas and Louisiana. See EVAPORITE, SALINE; GYPSUM. [EDWARD C. T. CHAO]

## Animal evolution

The theory that modern animals are the modified descendants of animals that formerly existed and that these earlier organisms descended from still earlier and different forms. Evidence for animal evolution should, where possible, be drawn from fossils representing actual ancestors. However, even for groups with hard skeletal parts the fossil record is far from complete. In addition, many types are soft-bodied and hence not preserved as fossils. As a result, much of the history of evolution must be deduced from study of existing forms. An increasing amount of biochemical evidence of animal relationship is accumulating, but reliance is placed mainly on comparison of adult structures and on embryonic and larval development. It was once assumed that embryos recapitulated the phylogeny of the race; this theory is largely abandoned today, but comparison of patterns of development and of larval types is of great value. The evidence, drawn from the various sources cited above, indicates that animals have evolved according to the evolutionary scheme shown in Fig. 1. See EVOLUTION, ORGANIC; FOSSIL; PALEONTOLOGY.

**Lower animals.** There are no definitive characters which apply to all supposed animals other than the fact that they are cellular or multicellular organisms which, unlike plants, do not manufacture their own food materials. It is often assumed that all such animals form a single evolutionary stock, advancing from single-celled forms, the Protozoa, through a colonial stage from which the sponges, the Parazoa, are an offshoot, to the level of the Metazoa. It is reasonable to believe that these all derive ultimately from single-celled flagellated plants, but there is no guarantee that they form an evolutionary unit. The Protozoa include the flagellates, the Mastigophora; the amebas and their relatives, the Sarcodina (Rhizopoda); the parasitic Sporozoa; and the complexly built Ciliophora. No one of the last three appears to be particularly related to any other. The Mastigophora seem to be a miscellaneous collection of flagellates which may have independently of one another, lost their food-manufacturing potentialities. The sponges seem to be derived from one peculiar type of collar-bearing flagellates, quite unrelated to typical protozoans. Metazoans show no indication of relationship to sponges or to protozoans in general.

**Early metazoan history.** In contrast with doubts regarding lower forms, there is essential unanimity

Fig. 1. (Opposite page) Evolution of animal groups. (From G. B. Moment, *General Zoology*, 2d ed., Houghton Mifflin, 1967; used by permission)