

CHAPTER

3

Minerals

Pick up any rock and look at it carefully. You will probably see small, differently colored specks like those in granite (Fig. 3–1). Each speck is a mineral. A **rock** is an aggregate of **minerals**. Some rocks are made of only one mineral, but most contain two to five abundant minerals plus minor amounts of several others.

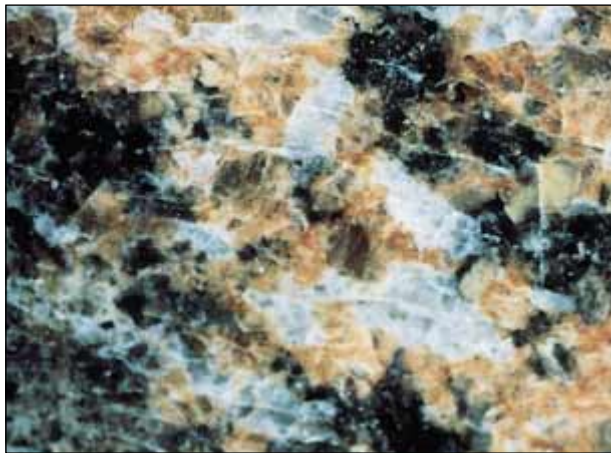
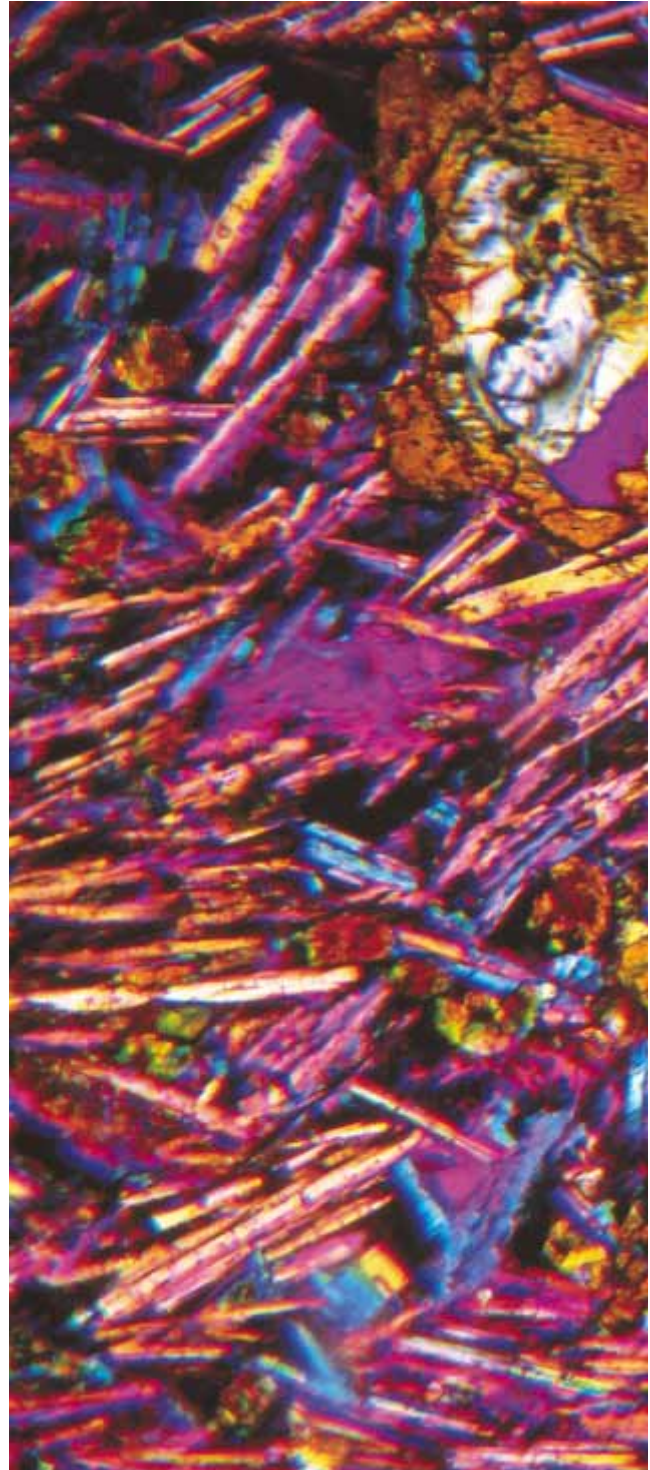
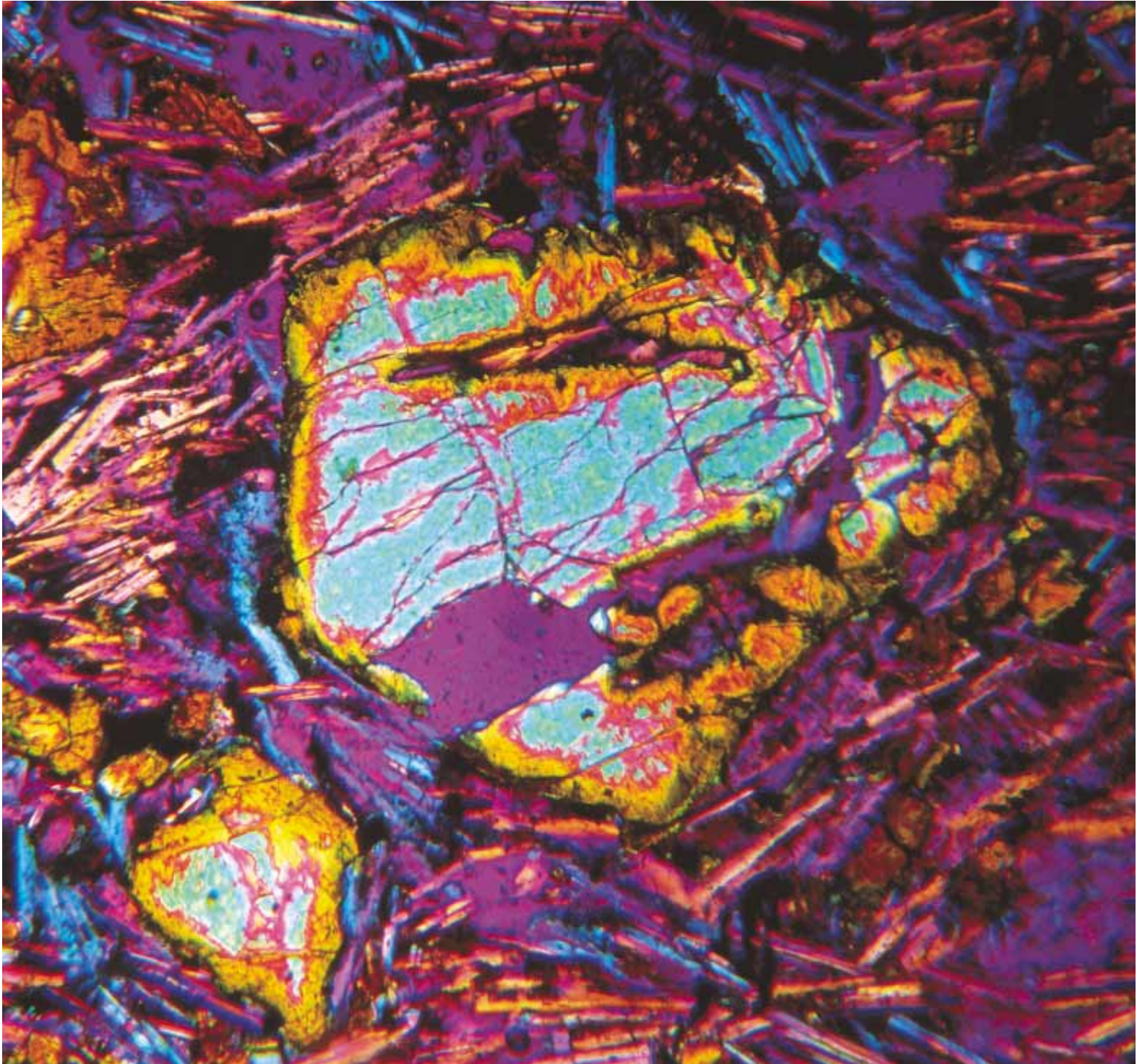


Figure 3–1 Each of the differently colored grains in this granite is a different mineral. The pink grains are feldspar; the black ones are biotite, and the glassy-white ones are quartz.



A sample of basalt, one of the most abundant rocks in the Earth's crust, viewed through a microscope. The intense colors are produced by polarized light. (© 1997 Kent Wood)



► 3.1 WHAT IS A MINERAL?

A mineral is a naturally occurring inorganic solid with a characteristic chemical composition and a crystalline structure. Chemical composition and crystalline structure are the two most important properties of a mineral: They distinguish any mineral from all others. Before discussing them, however, let us briefly consider the other properties of minerals described by this definition.

NATURAL OCCURRENCE

A synthetic diamond can be identical to a natural one, but it is not a true mineral because a mineral must form by natural processes. Like diamond, most gems that occur naturally can also be manufactured by industrial processes. Natural gems are valued more highly than manufactured ones. For this reason, jewelers should always tell their customers whether a gem is natural or artificial, and they usually preface the name of a manufactured gem with the term *synthetic*.

INORGANIC SOLID

Organic substances are made up mostly of carbon that is chemically bonded to hydrogen or other elements. Although organic compounds can be produced in laboratories and by industrial processes, plants and animals create most of the Earth's organic material. In contrast, inorganic compounds do not contain carbon-hydrogen bonds and generally are not produced by living organisms. All minerals are inorganic and most form independently of life. An exception is the calcite that forms limestone. Limestone is commonly composed of the shells of dead corals, clams, and similar marine organisms. Shells, in turn, are made of the mineral calcite or a similar mineral called aragonite. Although produced by organisms and containing carbon, the calcite and aragonite are true minerals.

► 3.2 ELEMENTS, ATOMS, AND THE CHEMICAL COMPOSITION OF MINERALS

To consider the chemical composition and crystalline structure of minerals, we must understand the nature of chemical **elements**—the fundamental components of matter. An element cannot be broken into simpler particles by ordinary chemical processes. Most common minerals consist of a small number—usually two to five—of different chemical elements.

A total of 88 elements occur naturally in the Earth's crust. However, eight elements—oxygen, silicon, alu-

minum, iron, calcium, magnesium, potassium, and sodium—make up more than 98 percent of the crust (Table 3–1).

A complete list of all elements is given in Table 3–2. Each element is represented by a one- or two-letter symbol, such as O for oxygen and Si for silicon. The table shows a total of 108 elements, not 88, because 20 elements are produced in nuclear reactors but do not occur naturally.

An **atom** is the basic unit of an element. An atom is tiny; the diameter of the average atom is about 10^{-10} meters (1/10,000,000,000). A single copper penny contains about 1.56×10^{22} (1.56 followed by 22 zeros) copper atoms. An atom consists of a small, dense, positively charged center called a **nucleus** surrounded by negatively charged **electrons** (Fig. 3–2).

An electron is a fundamental particle; it is not made up of smaller components. An electron orbits the nucleus, but not in a clearly defined path like that of the Earth around the Sun. Rather, an electron travels in a rapidly undulating path and is usually portrayed as a cloud of negative charge surrounding the nucleus. Electrons concentrate in spherical layers, or *shells*, around the nucleus. Each shell can hold a certain number of electrons.

The nucleus is made up of several kinds of particles; the two largest are positively charged **protons** and uncharged **neutrons**. A neutral atom contains equal numbers of protons and electrons. Thus, the positive and negative charges balance each other so that a neutral atom has no overall electrical charge.

An atom is most stable when its outermost shell is completely filled with electrons. But in their neutral

Table 3–1 • THE EIGHT MOST ABUNDANT CHEMICAL ELEMENTS IN THE EARTH'S CRUST

	WEIGHT PERCENT	ATOM PERCENT	VOLUME PERCENT*
O	46.60	62.55	93.8
Si	27.72	21.22	0.9
Al	8.13	6.47	0.5
Fe	5.00	1.92	0.4
Ca	3.63	1.94	1.0
Na	2.83	2.64	1.3
K	2.59	1.42	1.8
Mg	2.09	1.84	0.3
Total	98.59	100.00	100.00

From *Principles of Geochemistry* by Brian Mason and Carleton B. Moore. Copyright © 1982 by John Wiley & Sons, Inc.

*These numbers will vary somewhat as a function of the ionic radii chosen for the calculations.

Table 3–2 • THE PERIODIC TABLE

Groups of Main-Group Elements																										
1		2																3	4	5	6	7	8			
1	H 1																									He 2
2	Li 3	Be 4															B 5	C 6	N 7	O 8	F 9	Ne 10				
3	Na 11	Mg 12	Transition Elements														Al 13	Si 14	P 15	S 16	Cl 17	Ar 18				
4	K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36								
5	Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54								
6	Cs 55	Ba 56	* La 57	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86								
7	Fr 87	Ra 88	† Ac 89	Unq 104	Unp 105	Unh 106	Uns 107	108	Une 109																	

*Lanthanoids

Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------	----------

†Actinoids

Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103
----------	----------	---------	----------	----------	----------	----------	----------	----------	----------	-----------	-----------	-----------	-----------

Of the 108 elements that appear here, only 88 occur naturally in the Earth's crust. The other 20 are synthetic. The eight most abundant elements are shaded in orange. Elements with filled outer electron shells are shaded in violet.

states, most atoms do not have a filled outer shell. Such an atom may fill its outer shell by acquiring extra electrons until the shell becomes full. Alternatively, an atom may give up electrons until the outermost shell becomes empty. In this case, the next shell in, which is full, then becomes the outermost shell. When an atom loses one or more electrons, its protons outnumber its electrons and it develops a positive charge. If an atom gains one or more extra electrons, it becomes negatively charged. A charged atom is called an **ion**.

A positively charged ion is a **cation**. All of the abundant crustal elements except oxygen release electrons to become cations, as shown in Table 3–3. For example, each potassium atom (K) loses one electron to form a cation with a charge of 1+. Each silicon atom loses four electrons, forming a cation with a 4+ charge. In contrast,

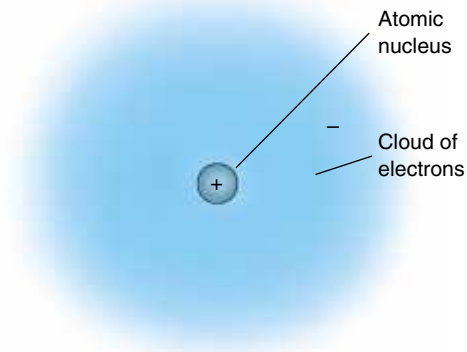


Figure 3–2 An atom consists of a small, dense, positive nucleus surrounded by a much larger cloud of negative electrons.

Table 3–3 • THE MOST COMMON IONS OF THE EIGHT MOST ABUNDANT CHEMICAL ELEMENTS IN THE EARTH’S CRUST

ELEMENT	CHEMICAL SYMBOL	COMMON ION(S)
Oxygen	O	O ^{2–}
Silicon	Si	Si ⁴⁺
Aluminum	Al	Al ³⁺
Iron	Fe	Fe ²⁺ and Fe ³⁺
Calcium	Ca	Ca ²⁺
Magnesium	Mg	Mg ²⁺
Potassium	K	K ¹⁺
Sodium	Na	Na ¹⁺

oxygen *gains* two extra electrons to acquire a 2– charge. Atoms with negative charges are called **anions**.

Atoms and ions rarely exist independently. Instead, they unite to form **compounds**. The forces that hold atoms and ions together to form compounds are called **chemical bonds** (see the “Focus On” box entitled “Chemical Bonds”).

Most minerals are compounds. When ions bond together to form a mineral, they do so in proportions so that the total number of negative charges exactly balances the total number of positive charges. Thus, minerals are always electrically neutral. For example, the mineral quartz proportionally consists of one (4+) silicon cation and two (2–) oxygen anions.

Recall that a mineral has a definite chemical composition. A substance with a definite chemical composition is made up of chemical elements that are bonded together in definite proportions. Therefore, the composition can be expressed as a chemical formula, which is written by combining the symbols of the individual elements.

A few minerals, such as gold and silver, consist of only a single element. Their chemical formulas, respectively, are Au (the symbol for gold) and Ag (the symbol for silver). Most minerals, however, are made up of two to five essential elements. For example, the formula of quartz is SiO₂: It consists of one atom of silicon (Si) for every two of oxygen (O). Quartz from anywhere in the Universe has that exact composition. If it had a different composition, it would be some other mineral. The compositions of some minerals, such as quartz, do not vary by even a fraction of a percent. The compositions of other minerals vary slightly, but the variations are limited, as explained in Section 3.7.

The 88 elements that occur naturally in the Earth’s crust can combine in many ways to form many different

minerals. In fact, about 3500 minerals are known. However, the eight abundant elements commonly combine in only a few ways. As a result, only nine **rock-forming minerals** (or mineral “groups”) make up most rocks of the Earth’s crust. They are olivine, pyroxene, amphibole, mica, the clay minerals, quartz, feldspar, calcite, and dolomite.

► 3.3 CRYSTALS: THE CRYSTALLINE NATURE OF MINERALS

A **crystal** is any substance whose atoms are arranged in a regular, periodically repeated pattern. All minerals are crystalline. The mineral halite (common table salt) has the composition NaCl: one sodium ion (Na⁺) for every chlorine ion (Cl[–]). Figure 3–3a is an “exploded” view of the ions in halite. Figure 3–3b is more realistic, showing the ions in contact. In both sketches the sodium and chlorine ions alternate in orderly rows and columns intersecting at right angles. This arrangement is the **crystalline structure** of halite.

Think of a familiar object with an orderly, repetitive pattern, such as a brick wall. The rectangular bricks repeat themselves over and over throughout the wall. As a result, the whole wall also has the shape of a rectangle or some modification of a rectangle. In every crystal, a small group of atoms, like a single brick in a wall, repeats itself over and over. This small group of atoms is called a **unit cell**. The unit cell for halite is shown in Figure 3–3a. If you compare Figures 3–3a and 3–3b, you will notice that the simple halite unit cell repeats throughout the halite crystal.

Most minerals initially form as tiny crystals that grow as layer after layer of atoms is added to their surfaces. A halite crystal might grow, for example, as salty seawater evaporates from a tidal pool. At first, a tiny grain might form, similar to the sketch of halite in Figure 3–3b. This model shows a halite crystal containing 125 atoms; it would be only about one millionth of a millimeter long on each side. As evaporation continued, more and more sodium and chlorine ions would precipitate onto the faces of the growing crystal. Minerals crystallize from cooling magma in a similar manner.

The shape of a large, well-formed crystal like that of halite in Figure 3–3c is determined by the shape of the unit cell and the manner in which the crystal grows. For example, it is obvious from Figure 3–4a that the stacking of small cubic unit cells can produce a large cubic crystal. Figure 3–4b shows that a different kind of stacking of the same cubes can also produce an eight-sided crystal, called an octahedron. Halite can crystallize as a cube or as an octahedron. All minerals consist of unit

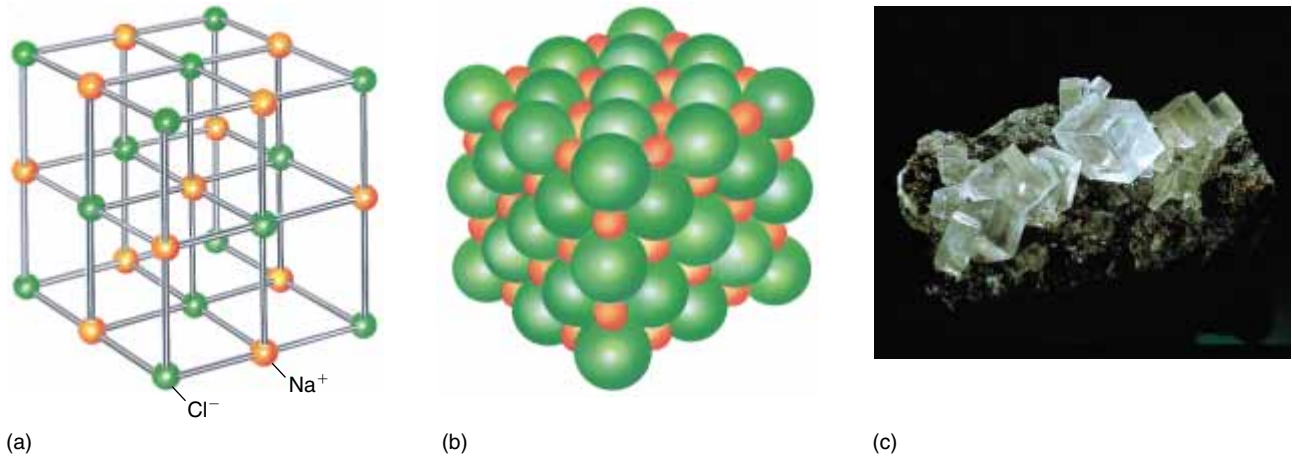


Figure 3-3 (a and b) The orderly arrangement of sodium and chlorine ions in halite. (c) Halite crystals. The crystal model in (a) is exploded so that you can see into it; the ions are actually closely packed as in (b). Note that ions in (a) and (b) form a cube, and the crystals in (c) are also cubes. (c, American Museum of Natural History)

cells stacked face to face as in halite, but not all unit cells are cubic.

A **crystal face** is a planar surface that develops if a crystal grows freely in an uncrowded environment. The sample of halite in Figure 3-3c has well-developed crystal faces. In nature, the growth of crystals is often impeded by adjacent minerals that are growing simultaneously or that have formed previously. For this reason, minerals rarely show perfect development of crystal faces.

▶ 3.4 PHYSICAL PROPERTIES OF MINERALS

How does a geologist identify a mineral in the field? Chemical composition and crystal structure distinguish each mineral from all others. For example, halite always consists of sodium and chlorine in a one-to-one ratio, with the atoms arranged in a cubic fashion. But if you pick up a crystal of halite, you cannot see the ions. You

(continued on p. 44)

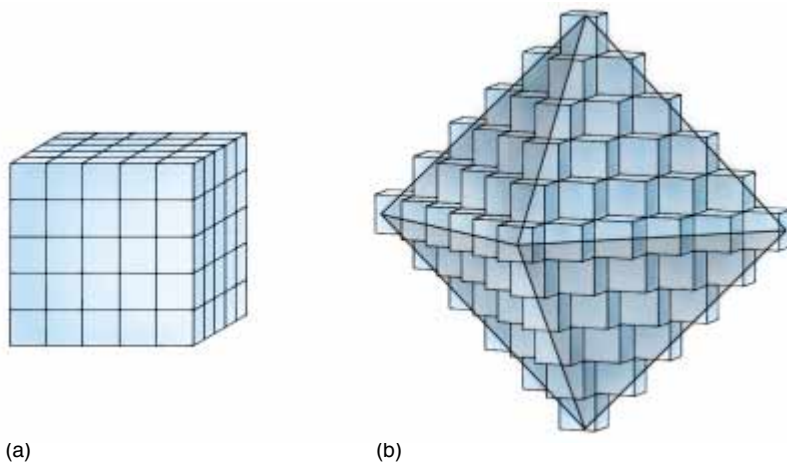


Figure 3-4 Both a cubic crystal (a) and an “octahedron” (b) can form by different kinds of stacking of identical cubes.

F O C U S O N

CHEMICAL BONDS

Electrons concentrate in **shells** around the nucleus of an atom (Fig. 1). The laws of quantum physics allow only certain shells, or energy levels, to exist around a nucleus. Electrons can only occupy those shells and cannot orbit in areas between shells.

Look at the periodic table (Table 3–2). The elements in the right-hand column, colored blue, have a filled outer shell in their normal, neutral state. Those elements are stable and chemically nonreactive because their outer electron shells are full. Other elements gain or lose electrons so that they acquire a filled outer shell like those shaded in blue.

For example, sodium has one electron *more* than a filled outer shell. Therefore, it tends to give up one electron. When it loses that electron, its outer shell is perfectly filled, but it becomes a positively charged cation because it then has one more proton than it has electrons. Oxygen acquires a filled shell by gaining two electrons and forming an anion. The common anions and cations of the eight abundant elements are shown in Table 3–3.

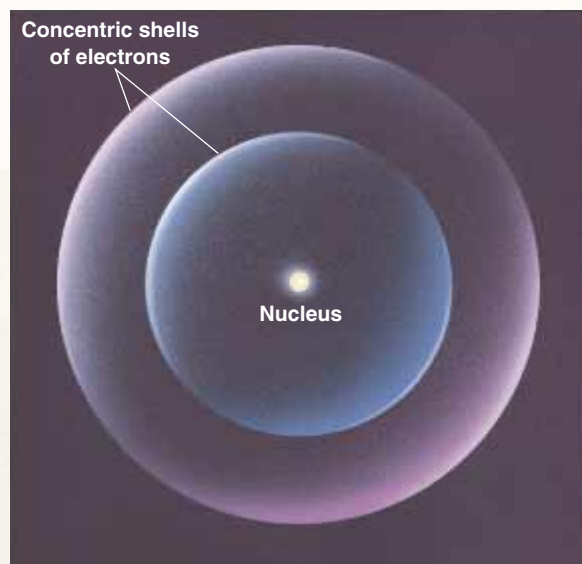


Figure 1 Electrons concentrate in spherical layers, or shells, around the nucleus of an atom.

Four types of chemical bonds are found in minerals: ionic, covalent, metallic, and van der Waals forces.

Ionic Bonds

Cations and anions are attracted by their opposite electronic charges and thus bond together. This union is called an **ionic bond**. An ionic compound (made up of two or more ions) is neutral because the positive and negative charges balance each other. For example, when sodium and chlorine form an ionic bond, the sodium atom loses one electron to become a cation and chlorine gains one to become an anion. When they combine, the +1 charge balances the –1 charge (Fig. 2).

Covalent Bonds

A **covalent bond** develops when two or more atoms share their electrons to produce the effect of filled outer electron shells. For example, carbon needs four electrons to fill its outermost shell. It can achieve this by forming four covalent bonds with four adjacent carbon atoms. It “gains” four electrons by sharing one with another carbon atom at each of the four bonds. Diamond consists of a three-dimensional network of carbon atoms bonded into a network of tetrahedra, similar to the framework structure of quartz (Fig. 3). The strength and homogeneity of the bonds throughout the crystal make diamond the hardest of all minerals.

In most minerals, the bonds between atoms are partly covalent and partly ionic. The combined characteristics of the different bond types determine the physical properties of those minerals.

Metallic Bonds

In a **metallic bond**, the outer electrons are loose; that is, they are not associated with particular atoms. The metal atoms sit in a “sea” of outer-level electrons that are free to move from one atom to another. That arrangement allows the nuclei to pack together as closely as possible, resulting in the characteristic high density of metals and metallic minerals, such as pyrite. Because the electrons are free to move through the

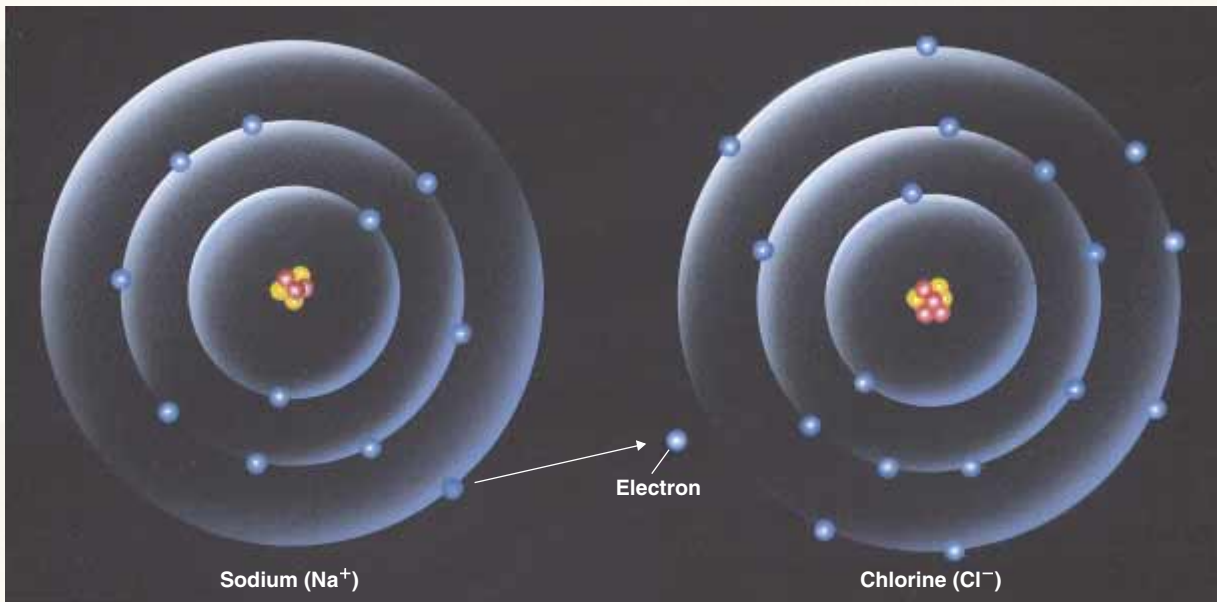


Figure 2 When sodium and chlorine atoms combine, sodium loses one electron, becoming a cation, Na^+ . Chlorine acquires the electron to become an anion, Cl^- .

entire crystal, metallic minerals are excellent conductors of electricity and heat.

Van der Waals Forces

Weak electrical forces called **van der Waals forces** also bond molecules together. These weak bonds result from an uneven distribution of electrons around individual molecules, so that one portion of a molecule may have a greater density of negative charge while another portion has a partial positive charge. Because van der Waals forces are weak, minerals in which these bonds are important, such as talc and graphite, tend to be soft and cleave easily along planes of van der Waals bonds.

DISCUSSION QUESTION

Why do some minerals, such as native gold, silver, and graphite, conduct electricity, whereas others, such as quartz and feldspar, do not? Discuss relationships among other physical properties of minerals and the types of chemical bonds found in those minerals.

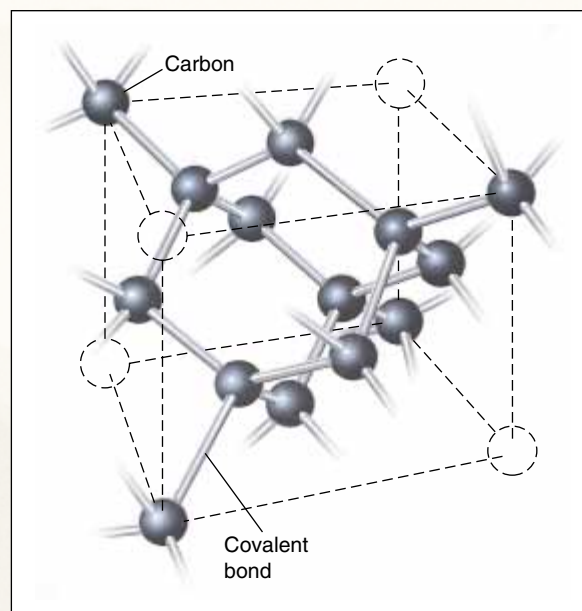


Figure 3 Carbon atoms in diamond form a tetrahedral network similar to that of quartz.



(a)



(c)



(b)

Figure 3-5 (a) *Equant* garnet crystals have about the same dimensions in all directions. (b) Asbestos is *fibrous*. (c) Kyanite forms *bladed* crystals. (Geoffrey Sutton)

could identify a sample of halite by measuring its chemical composition and crystal structure using laboratory procedures, but such analyses are expensive and time-consuming. Instead, geologists commonly identify minerals by visual recognition, and they confirm the identification with simple tests.

Most minerals have distinctive appearances. Once you become familiar with common minerals, you will recognize them just as you recognize any familiar object. For example, an apple just *looks* like an apple, even though apples come in many colors and shapes. In the same way, quartz looks like quartz to a geologist. The

color and shape of quartz may vary from sample to sample, but it still looks like quartz. Some minerals, however, look enough alike that their physical properties must be examined further to make a correct identification. Geologists commonly use physical properties such as crystal habit, cleavage, and hardness to identify minerals.

CRYSTAL HABIT

Crystal habit is the characteristic shape of a mineral and the manner in which aggregates of crystals grow. If a



(a)



(b)

Figure 3-6 (a) *Prismatic* quartz grows as elongated crystals. (b) *Massive* quartz shows no characteristic shape. (Arkansas Geological Commission, J. M. Howard, Photographer)



Figure 3-7 A photomicrograph of a thin slice of granite. When crystals grow simultaneously, they commonly interlock and show no characteristic habit. To make this photo, a thin slice of granite was cut with a diamond saw, glued to a microscope slide, and ground to a thickness of 0.02 millimeters. Most minerals are transparent when such thin slices are viewed through a microscope.

crystal grows freely, it develops a characteristic shape controlled by the arrangement of its atoms, as in the cubes of halite shown in Figure 3-3c. Figure 3-5 shows three common minerals with different crystal habits. Some minerals occur in more than one habit. For example, Figure 3-6a shows quartz with a prismatic (pencil-shaped) habit, and Figure 3-6b shows massive quartz.

When crystal growth is obstructed by other crystals, a mineral cannot develop its characteristic habit. Figure 3-7 is a photomicrograph (a photo taken through a microscope) of a thin slice of granite in which the crystals fit like pieces of a jigsaw puzzle. This interlocking texture developed because some crystals grew around others as the magma solidified.

CLEAVAGE

Cleavage is the tendency of some minerals to break along flat surfaces. The surfaces are planes of weak bonds in the crystal. Some minerals, such as mica and graphite, have one set of parallel cleavage planes (Fig. 3-8). Others have two, three, or even four different sets, as shown in Figure 3-9. Some minerals, like the micas, have excellent cleavage. You can peel sheet after sheet from a mica crystal as if you were peeling layers from an onion. Others have poor cleavage. Many minerals have no cleavage at all because they have no planes of

weak bonds. The number of cleavage planes, the quality of cleavage, and the angles between cleavage planes all help in mineral identification.

A flat surface created by cleavage and a crystal face can appear identical because both are flat, smooth surfaces. However, a cleavage surface is duplicated when a crystal is broken, whereas a crystal face is not. So if you are in doubt, break the sample with a hammer—unless, of course, you want to save it.

FRACTURE

Fracture is the pattern in which a mineral breaks other than along planes of cleavage. Many minerals fracture into characteristic shapes. Conchoidal fracture creates smooth, curved surfaces (Fig. 3-10). It is characteristic of quartz and olivine. Glass, although not a mineral because it has no crystalline structure, also typically fractures in a conchoidal pattern. Some minerals break into splintery or fibrous fragments. Most fracture into irregular shapes.

HARDNESS

Hardness is the resistance of a mineral to scratching. It is easily measured and is a fundamental property of each mineral because it is controlled by bond strength between the atoms in the mineral. Geologists commonly



Figure 3-8 Cleavage in mica. This large crystal is the variety of mica called muscovite. (Geoffrey Sutton)



Figure 3-9 Some minerals have more than one cleavage plane. (a) Feldspar has two cleavages intersecting at right angles. (b) Calcite has three cleavage planes. (c) Fluorite has four cleavage planes. (Arthur R. Hill, Visuals Unlimited)

gauge hardness by attempting to scratch a mineral with a knife or other object of known hardness. If the blade scratches the mineral, the mineral is softer than the knife. If the knife cannot scratch the mineral, the mineral is harder.

To measure hardness more accurately, geologists use a scale based on ten minerals, numbered 1 through 10. Each mineral is harder than those with lower numbers on the scale, so 10 (diamond) is the hardest and 1 (talc) is the softest. The scale is known as the **Mohs hardness scale** after F. Mohs, the Austrian mineralogist who developed it in the early nineteenth century.

The Mohs hardness scale shows, for example, that a mineral scratched by quartz but not by orthoclase has a hardness between 6 and 7 (Table 3-4). Because the min-

erals of the Mohs scale are not always handy, it is useful to know the hardness values of common materials. A fingernail has a hardness of slightly more than 2, a copper penny about 3, a pocketknife blade slightly more than 5, window glass about 5.5, and a steel file about 6.5. If you practice with a knife and the minerals of the Mohs scale, you can develop a “feel” for minerals with hardnesses of 5 and under by how easily the blade scratches them.

When testing hardness, it is important to determine whether the mineral has actually been scratched by the object, or whether the object has simply left a trail of its own powder on the surface of the mineral. To check, simply rub away the powder trail and feel the surface of the mineral with your fingernail for the groove of the



Figure 3-10 Quartz typically fractures along smoothly curved surfaces, called conchoidal fractures. This sample is smoky quartz. (Breck P. Kent)

Table 3-4 • THE MINERALS OF THE MOHS HARDNESS SCALE

MINERALS OF MOHS SCALE	COMMON OBJECTS
1. Talc	
2. Gypsum	Fingernail
3. Calcite	Copper penny
4. Fluorite	
5. Apatite	Knife blade
	Window glass
6. Orthoclase	
7. Quartz	Steel file
8. Topaz	
9. Corundum	
10. Diamond	

scratch. Fresh, unweathered mineral surfaces must be used in hardness measurements because weathering often produces a soft rind on minerals.

SPECIFIC GRAVITY

Specific gravity is the weight of a substance relative to that of an equal volume of water. If a mineral weighs 2.5 times as much as an equal volume of water, its specific gravity is 2.5. You can estimate a mineral's specific gravity simply by hefting a sample in your hand. If you practice with known minerals, you can develop a feel for specific gravity. Most common minerals have specific gravities of about 2.7. Metals have much greater specific gravities; for example, gold has the highest specific gravity of all minerals, 19. Lead is 11.3, silver is 10.5, and copper is 8.9.

COLOR

Color is the most obvious property of a mineral, but it is commonly unreliable for identification. Color would be a reliable identification tool if all minerals were pure and had perfect crystal structures. However, both small amounts of chemical impurities and imperfections in crystal structure can dramatically alter color. For example, corundum (Al_2O_3) is normally a cloudy, translucent, brown or blue mineral. Addition of a small amount of chromium can convert corundum to the beautiful, clear, red gem known as ruby. A small quantity of iron or titanium turns corundum into the striking blue gem called sapphire.

STREAK

Streak is the color of a fine powder of a mineral. It is observed by rubbing the mineral across a piece of unglazed porcelain known as a streak plate. Many minerals leave a streak of powder with a diagnostic color on the plate. Streak is commonly more reliable than the color of the mineral itself for identification.

LUSTER

Luster is the manner in which a mineral reflects light. A mineral with a metallic look, irrespective of color, has a metallic luster. The luster of nonmetallic minerals is usually described by self-explanatory words such as glassy, pearly, earthy, and resinous.

OTHER PROPERTIES

Properties such as reaction to acid, magnetism, radioactivity, fluorescence, and phosphorescence can be

characteristic of specific minerals. Calcite and some other carbonate minerals dissolve rapidly in acid, releasing visible bubbles of carbon dioxide gas. Minerals containing radioactive elements such as uranium emit radioactivity that can be detected with a scintillometer. Fluorescent materials emit visible light when they are exposed to ultraviolet light. Phosphorescent minerals continue to emit light after the external stimulus ceases.

▶ 3.5 ROCK-FORMING MINERALS, ACCESSORY MINERALS, GEMS, ORE MINERALS, AND INDUSTRIAL MINERALS

Although about 3500 minerals are known to exist in the Earth's crust, only a small number—between 50 and 100—are important because they are common or valuable.

ROCK-FORMING MINERALS

The rock-forming minerals make up the bulk of most rocks in the Earth's crust. They are important to geologists simply because they are the most common minerals. They are olivine, pyroxene, amphibole, mica, the clay minerals, feldspar, quartz, calcite, and dolomite. The first six minerals in this list are actually mineral "groups," in which each group contains several varieties



Figure 3-11 Pyrite is a common accessory mineral. (American Museum of Natural History)



Figure 3-12 Sapphire is one of the most costly precious gems. (Smithsonian Institution)

with very similar chemical compositions, crystalline structures, and appearances. The rock-forming minerals are described in Section 3.6.

ACCESSORY MINERALS

Accessory minerals are minerals that are common but usually are found only in small amounts. Chlorite, garnet, hematite, limonite, magnetite, and pyrite are common accessory minerals (Fig. 3-11).



Figure 3-13 Topaz is a popular semiprecious gem. (American Museum of Natural History)

GEMS

A **gem** is a mineral that is prized primarily for its beauty, although some gems, like diamonds, are also used industrially. Depending on its value, a gem can be either precious or semiprecious. Precious gems include diamond, emerald, ruby, and sapphire (Fig. 3-12). Several varieties of quartz, including amethyst, agate, jasper, and tiger's eye, are semiprecious gems. Garnet, olivine, topaz, turquoise, and many other minerals sometimes occur as aesthetically pleasing semiprecious gems (Fig. 3-13).

ORE MINERALS

Ore minerals are minerals from which metals or other elements can be profitably recovered. A few, such as native gold and native silver, are composed of a single element. However, most metals are chemically bonded to anions. Copper, lead, and zinc are commonly bonded to sulfur to form the important ore minerals chalcopyrite, galena (Fig. 3-14), and sphalerite.

INDUSTRIAL MINERALS

Several minerals are industrially important, although they are not considered ore because they are mined for purposes other than the extraction of metals. Halite is mined for table salt, and gypsum is mined as the raw material for plaster and sheetrock. Apatite and other phosphorus minerals are sources of the phosphate fertilizers crucial to modern agriculture. Many limestones are made up of nearly pure calcite and are mined as the raw material of cement.



Figure 3-14 Galena is the most important ore of lead and commonly contains silver. (Ward's Natural Science Establishment, Inc.)

► 3.6 MINERAL CLASSIFICATION

Geologists classify minerals according to their anions (negatively charged ions). Anions can be either simple or complex. A simple anion is a single negatively charged ion, such as O^{2-} . Alternatively, two or more atoms can bond firmly together and acquire a negative charge to form a complex anion. Two common examples are the silicate, $(\text{SiO}_4)^{4-}$, and carbonate, $(\text{CO}_3)^{2-}$, complex anions.

Each mineral group (except the native elements) is named for its anion. For example, the oxides all contain O^{2-} , the silicates contain $(\text{SiO}_4)^{4-}$, and the carbonates contain $(\text{CO}_3)^{2-}$.

NATIVE ELEMENTS

About 20 elements occur naturally in their native states as minerals. Fewer than ten, however, are common enough to be of economic importance. Gold, silver, platinum, and copper are all mined in their pure forms. Iron is rarely found in its native state in the Earth's crust, but metallic iron is common in certain types of meteorites. Native iron and nickel are thought to comprise most of the Earth's core. Native sulfur, used to manufacture sulfuric acid, insecticides, fertilizer, and rubber, is mined from volcanic craters, where it is deposited from gases emanating from the vents (Fig. 3–15).

Pure carbon occurs as both graphite and diamond. The minerals have identical compositions but different crystalline structures and are called **polymorphs**, after the ancient Greek for “several forms.” Graphite is one of the softest minerals and is opaque and an electrical conductor. Diamond, the hardest mineral known, is transparent and an electrical insulator. The contrasting



Figure 3–15 Native sulfur is forming today in the vent of Ollagüe Volcano on the Chile–Bolivia border.

characteristics of graphite and diamond emphasize the importance of crystalline structure in determining the physical properties of minerals.

OXIDES

The oxides are a large group of minerals in which oxygen is combined with one or more metals. Oxide minerals are the most important ores of iron, manganese, tin, chromium, uranium, titanium, and several other industrial metals. Hematite (iron oxide, Fe_2O_3) occurs widely in many types of rocks and is the most abundant ore of iron. Although typically red in color, it occasionally occurs as black crystals used as semiprecious gems. Magnetite (Fe_3O_4), a naturally magnetic iron oxide, is another ore of iron. Spinel (MgAl_2O_4) often occurs as attractive red or blue crystals that are used as inexpensive, semiprecious gems. Synthetic spinels are also commonly used in jewelry. Ice, the oxide of hydrogen (H_2O), is a common mineral at the Earth's surface.

SULFIDES

Sulfide minerals consist of sulfur combined with one or more metals. Many sulfides are extremely important ore minerals. They are the world's major sources of copper, lead, zinc, molybdenum, silver, cobalt, mercury, nickel, and several other metals. The most common sulfides are pyrite (FeS_2), chalcopyrite (CuFeS_2), galena (PbS), and sphalerite (ZnS).

SULFATES

The sulfate minerals contain the sulfate complex anion $(\text{SO}_4)^{2-}$. Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and anhydrite (CaSO_4) are two important industrial sulfates used to manufacture plaster and sheetrock. Both form by evaporation of seawater or salty lake water.

PHOSPHATES

Phosphate minerals contain the complex anion $(\text{PO}_4)^{3-}$. Apatite, $\text{Ca}_5(\text{F,Cl,OH})(\text{PO}_4)_3$, is the substance that makes up both teeth and bones. Phosphate is an essential fertilizer in modern agriculture. It is mined from fossil bone beds near Tampa, Florida, and from great sedimentary apatite deposits in the northern Rocky Mountains.

CARBONATES

The complex carbonate anion $(\text{CO}_3)^{2-}$ is the basis of two common rock-forming minerals, calcite (CaCO_3)



(a)



(b)

Figure 3-16 Calcite (a) and dolomite (b) are two rock-forming carbonate minerals. (Ward's Natural Science Establishment, Inc.)

and dolomite $[\text{CaMg}(\text{CO}_3)_2]$ (Figs. 3-16a and 3-16b). Most limestone is composed of calcite, and dolomite makes up the similar rock that is also called dolomite or sometimes dolostone. Limestone is mined as a raw in-

gradient of cement. Aragonite is a polymorph of calcite that makes up the shells of many marine animals.

SILICATES

The silicate minerals contain the $(\text{SiO}_4)^{4-}$ complex anion. Silicates make up about 95 percent of the Earth's crust. They are so abundant for two reasons. First, silicon and oxygen are the two most plentiful elements in the crust. Second, silicon and oxygen combine readily. To understand the silicate minerals, remember four principles:

1. Every silicon atom surrounds itself with four oxygens. The bonds between each silicon and its four oxygens are very strong.
2. The silicon atom and its four oxygens form a pyramid-shaped structure called the **silicate tetrahedron** with silicon in the center and oxygens at the four corners (Fig. 3-17). The silicate tetrahedron has a 4- charge and forms the $(\text{SiO}_4)^{4-}$ complex anion. The silicate tetrahedron is the fundamental building block of all silicate minerals.

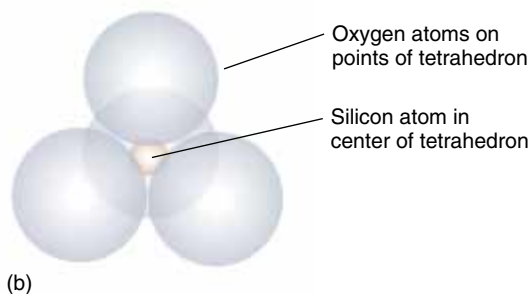
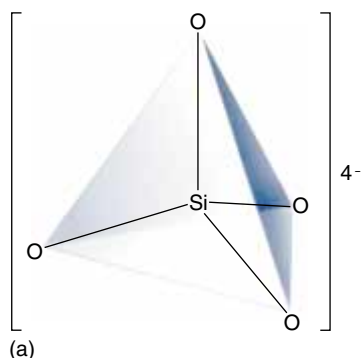

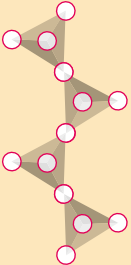
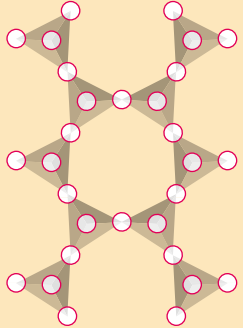
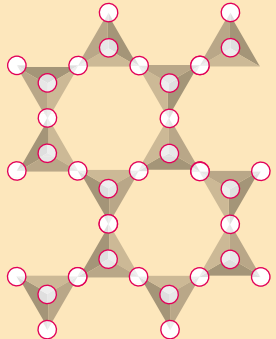
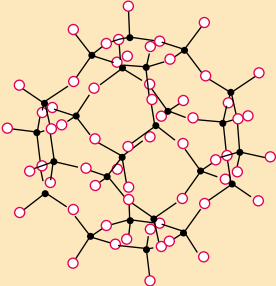


Figure 3-17 The silicate tetrahedron consists of one silicon atom surrounded by four oxygens. It is the fundamental building block of all silicate minerals. (a) A ball-and-stick representation. (b) A proportionally accurate model.

Figure 3-18 The five silicate structures are based on sharing of oxygens among silicate tetrahedra. (A) Independent tetrahedra share no oxygens. (B) In single chains, each tetrahedron shares two oxygens with adjacent tetrahedra, forming a chain. (C) A double chain is a pair of single chains that are crosslinked by additional oxygen sharing. (D) In the sheet silicates, each tetrahedron shares three oxygens with adjacent tetrahedra. (E) A three-dimensional silicate framework shares all four oxygens of each tetrahedron.

Class	Arrangement of SiO_4 tetrahedron	Unit composition	Mineral examples
A Independent tetrahedra		$(\text{SiO}_4)^{4-}$	Olivine: The composition varies between Mg_2SiO_4 and Fe_2SiO_4 .
B Single chains		$(\text{SiO}_3)^{2-}$	Pyroxene: The most common pyroxene is augite, $\text{Ca}(\text{Mg, Fe, Al}) (\text{Al, Si})_2\text{O}_6$.
C Double chains		$(\text{Si}_4\text{O}_{11})^{6-}$	Amphibole: The most common amphibole is hornblende, $\text{NaCa}_2(\text{Mg, Fe, Al})_5(\text{Si, Al})_8\text{O}_{22}(\text{OH})_2$.
D Sheet silicates		$(\text{Si}_2\text{O}_5)^{2-}$	Mica, clay minerals, chlorite, e.g.: muscovite $\text{KAl}_2(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH})_2$
E Framework silicates		SiO_2	Quartz: SiO_2 Feldspar: As an example, potassium feldspar is KAlSi_3O_8 .



(a)



(b)



(c)



(d)



(e)



(f)



(g)

Figure 3-19 The seven rock-forming silicate mineral groups. (a) Olivine. (Geoffrey Sutton) (b) Pyroxene. (© Jeffrey A. Scovil) (c) Amphibole. (© Jeffrey A. Scovil) (d) Black biotite is one common type of mica. White muscovite (Fig. 3-8) is the other. (e) Clay. (f) Feldspar; represented here by orthoclase feldspar. (Breck P. Kent) (g) Quartz. (© Jeffrey A. Scovil)

3. To make silicate minerals electrically neutral, other cations must combine with the silicate tetrahedra to balance their negative charges. (The lone exception is quartz, in which the positive charges on the silicons exactly balance the negative ones on the oxygens. How this occurs is described later.)
4. Silicate tetrahedra commonly link together by sharing oxygens. Thus, two tetrahedra may share a single oxygen, bonding the tetrahedra together.

Rock-Forming Silicate Minerals

The rock-forming silicates (and most other silicate minerals) fall into five classes, based on five ways in which tetrahedra share oxygens (Fig. 3-18). Each class contains at least one of the rock-forming mineral groups.

1. In independent tetrahedra silicates, adjacent tetrahedra do not share oxygens (Fig. 3-18A). **Olivine** is an independent tetrahedra mineral that occurs in small quantities in basalt of both continental and

oceanic crust (Fig. 3-19a). However, rocks composed mostly of olivine and pyroxene are thought to make up most of the mantle.

2. In the single-chain silicates, each tetrahedron links to two others by sharing oxygens, forming a continuous chain of tetrahedra (Fig. 3-18B). The **pyroxenes** are a group of similar minerals with single chain structures (Fig. 3-19b). Pyroxenes are a major component of both oceanic crust and the mantle and are also abundant in some continental rocks.
3. The double-chain silicates consist of two single chains crosslinked by the sharing of additional oxygens between them (Fig. 3-18C). The **amphiboles** (Fig. 3-19c) are a group of double-chain silicates with similar properties. They occur commonly in many continental rocks. One variety of amphibole grows as sharply pointed needles and is a type of asbestos.

Pyroxene and amphibole can resemble each other so closely that they are difficult to tell apart. Both groups have similar chain structures and simi-

lar chemical compositions. In addition, both commonly grow as pencil-shaped crystals.

4. In the sheet silicates, each tetrahedron shares oxygens with three others in the same plane, forming a continuous sheet (Fig. 3–18D). All of the atoms within each sheet are strongly bonded, but each sheet is only weakly bonded to those above and below. Therefore, sheet silicates have excellent cleavage. The **micas** are sheet silicates and typically grow as plate-shaped crystals, with flat surfaces (Fig. 3–19d). Mica is common in continental rocks. The **clay minerals** (Fig. 3–19e) are similar to mica in structure, composition, and platy habit. Individual clay crystals are so small that they can barely be seen with a good optical microscope. Most clay forms when other minerals weather at the Earth's surface. Thus, clay minerals are abundant near the Earth's surface and are an important component of soil and of sedimentary rocks.
5. In the framework silicates, each tetrahedron shares all four of its oxygens with adjacent tetrahedra (Fig. 3–18E). Because tetrahedra share oxygens in all directions, minerals with the framework structure tend to grow blocky crystals that have similar dimensions in all directions. **Feldspar** and **quartz** have framework structures.

The feldspars (Fig. 3–19f) make up more than 50 percent of the Earth's crust. The different varieties of feldspar are named according to whether potassium or a mixture of sodium and calcium is present in the mineral. **Orthoclase** is a common feldspar containing potassium. Feldspar containing calcium and/or sodium is called **plagioclase**. Plagioclase and orthoclase often look alike and can be difficult to tell apart.

Quartz is the only common silicate mineral that contains no cations other than silicon; it is pure SiO_2 (Fig. 3–19g). It has a ratio of one $4+$ silicon for every two $2-$ oxygens, so the positive and negative charges neutralize each other perfectly. Quartz is widespread and abundant in continental rocks but rare in oceanic crust and the mantle.

► 3.7 IONIC SUBSTITUTION

Ionic substitution is the replacement of one ion by another in the crystal structure of a mineral. Generally, one ion can substitute for another if the ions are of similar size and if their charges are within $1+$ or $1-$.

Many minerals show variations in composition because of ionic substitution, although the variation is restricted to well-defined limits for each mineral. For example, olivine can be pure Mg_2SiO_4 or pure Fe_2SiO_4 , and it can also have any proportion of magnesium (Mg) to iron (Fe) between the two extremes. As we mentioned earlier in this chapter, ionic substitution of small amounts of chromium for aluminum in the mineral corundum is responsible for the characteristic red color of ruby, and substitution of iron or titanium produces the blue of sapphire.

In the tetrahedral framework structure of potassium feldspar, one Al^{3+} ion substitutes for every fourth Si^{4+} . Because aluminum has only a $3+$ charge and silicon is $4+$, a charge of $1-$ develops for every fourth tetrahedron. One $1+$ potassium ion enters the feldspar structure to maintain electrical neutrality. Similar substitution of aluminum for silicon occurs in all other feldspars and in many other silicate minerals.

SUMMARY

Minerals are the substances that make up rocks. A mineral is a naturally occurring inorganic solid with a definite chemical composition and a crystalline structure. Each mineral consists of chemical elements bonded together in definite proportions, so that its chemical composition can be given as a chemical formula. The **crystalline structure** of a mineral is the orderly, periodically repeated arrangement of its atoms. A **unit cell** is a small structural and compositional module that repeats itself throughout a crystal. The shape of a crystal is determined by the shape and arrangement of its unit cells. Every mineral is distinguished from others by its chemical composition and crystal structure.

Most common minerals are easily recognized and identified visually. Identification is aided by observing a few physical properties, including **crystal habit**, **cleavage**, **fracture**, **hardness**, **specific gravity**, **color**, **streak**, and **luster**.

Although about 3500 minerals are known in the Earth's crust, only the nine **rock-forming mineral groups** are abundant in most rocks. They are **feldspar**, **quartz**, **pyroxene**, **amphibole**, **mica**, **the clay minerals**, **olivine**, **calcite**, and **dolomite**. The first seven on this list are **silicates**; their structures and compositions are based on the **silicate tetrahedron**, in which a silicon atom is surrounded by four oxygens to form a pyramid-shaped

structure. Silicate tetrahedra link together by sharing oxygens to form the basic structures of the silicate minerals. The silicates are the most abundant minerals because silicon and oxygen are the two most abundant elements in the Earth's crust and bond together readily to form the silicate tetrahedron. Two carbonate minerals, calcite and dolomite, are also sufficiently abundant to be called rock-forming minerals.

Accessory minerals are commonly found, but in small amounts. **Ore minerals**, **industrial minerals**, and **gems** are important for economic reasons. Many minerals show compositional variation because of ionic substitution. In general, one element can substitute for another if the two are similar in charge and size.

Rock-Forming Mineral Groups

Feldspar	Amphibole	Olivine
Quartz	Mica	Calcite
Pyroxene	Clay minerals	Dolomite

KEY WORDS

mineral 36	cation 39	crystal face 41	luster 47
element 38	anion 40	crystal habit 44	accessory mineral 48
atom 38	compound 40	cleavage 45	gem 48
nucleus 38	chemical bond 40	fracture 45	ore mineral 48
electron 38	rock-forming mineral 40	hardness 45	polymorph 49
proton 38	crystal 40	Mohs hardness scale 46	silicates 50
neutron 38	crystalline structure 40	specific gravity 47	silicate tetrahedron 50
ion 39	unit cell 40	streak 47	ionic substitution 53

REVIEW QUESTIONS

- What properties distinguish minerals from other substances?
- Explain why oil and coal are not minerals.
- What does the chemical formula for quartz, SiO_2 , tell you about its chemical composition? What does KAlSi_3O_8 tell you about orthoclase feldspar?
- What is an atom? An ion? A cation? An anion? What roles do they play in minerals?
- What is a chemical bond? What role do chemical bonds play in minerals?
- Every mineral has a crystalline structure. What does this mean?
- What factors control the shape of a well-formed crystal?
- What is a crystal face?
- What conditions allow minerals to grow well-formed crystals? What conditions prevent their growth?
- List and explain the physical properties of minerals most useful for identification.
- Why do some minerals have cleavage and others do not? Why do some minerals have more than one set of cleavage planes?
- Why is color often an unreliable property for mineral identification?
- List the rock-forming mineral groups. Why are they called "rock-forming"? Which are silicates? Why are so many of them silicates?
- Draw a three-dimensional view of a single silicate tetrahedron. Draw the five different arrangements of tetrahedra found in the rock-forming silicate minerals. How many oxygen ions are shared between adjacent tetrahedra in each of the five configurations?
- Make a table with two columns. In the left column list the basic silicate structures. In the right column list one or more rock-forming minerals with each structure.

DISCUSSION QUESTIONS

1. Diamond and graphite are two minerals with identical chemical compositions, pure carbon (C). Diamond is the hardest of all minerals, and graphite is one of the softest. If their compositions are identical, why do they have such profound differences in physical properties?
2. List the eight most abundant chemical elements in the Earth's crust. Are any unfamiliar to you? List familiar elements that are not among the eight. Why are they familiar?
3. Table 3–1 shows that silicon and oxygen together make up nearly 75 percent by weight of the Earth's crust. But silicate minerals make up more than 95 percent of the crust. Explain the apparent discrepancy.
4. Quartz is SiO_2 . Why does no mineral exist with the composition SiO_3 ?
5. If you were given a crystal of diamond and another of quartz, how would you tell which is diamond?
6. Would you expect minerals found on the Moon, Mars, or Venus to be different from those of the Earth's crust? Explain your answer.