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Crystals of amethyst, a variety of quartz. The planar surfaces are crystal faces, whose geometries are determined by the underlying arrangement of the atoms that make up the crystals. [Breck P. Kent.]



Minerals: Building Blocks of Rocks

“Everything should be made as simple as possible, but no simpler.”

ALBERT EINSTEIN

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In Chapter 2, we saw how plate tectonics describes Earth’s large-scale structure and dynamics, but we touched only briefly on the wide variety of materials that appear in plate tectonic settings. **In this chapter and the next, we focus on rocks, the records of geologic processes, and on minerals, the building blocks of rocks.**

Rocks and minerals help determine various parts of the Earth system, much as concrete, steel, and plastic determine the structure, design, and architecture of large buildings. To tell Earth’s story accurately, geologists often adopt a “Sherlock Holmes” approach: they use current evidence to deduce the processes and events that occurred in the past at some particular place. The kinds of minerals found in volcanic rocks, for example,

give evidence of eruptions that brought molten rock, at temperatures perhaps as high as 1000°C, to Earth’s surface. The minerals of a granite reveal that it crystallized deep in the crust under the very high temperatures and pressures that occur when two continental plates collide and form mountains like the Himalayas. Understanding the geology of a region allows us to make informed guesses about where undiscovered deposits of economically important mineral resources might lie.

We turn now to the focus of this chapter: **mineralogy**—the branch of geology that studies the composition, structure, appearance, stability, occurrence, and associations of minerals.



What Are Minerals?

Minerals are the building blocks of rocks: with the proper tools, most rocks can be separated into their constituent minerals. A few kinds of rocks, such as limestone,



Figure 3.1 The mineral calcite is found in the shells of many organisms, such as foraminifera. [left: Lester V. Bergman/Corbis; right: Cushman Foundation for Foraminiferal Research, 1987.]

contain only a single mineral (in this case, calcite). Other rocks, such as granite, are made of several different minerals. To identify and classify the many kinds of rocks that compose the Earth and understand how they formed, we must know about minerals.

Geologists define a **mineral** as a *naturally occurring, solid crystalline substance, generally inorganic, with a specific chemical composition*. Minerals are homogeneous: they cannot be divided by mechanical means into smaller components.

Let us examine each part of our definition of a mineral in a little more detail.

Naturally Occurring . . . To qualify as a mineral, a substance must be found in nature. Diamonds mined from the Earth in South Africa are minerals. Synthetic versions produced in industrial laboratories are not considered to be minerals. Nor are the thousands of laboratory products invented by chemists.

Solid Crystalline Substance . . . Minerals are solid substances—they are neither liquids nor gases. When we say that a mineral is *crystalline*, we mean that the tiny particles of matter, or atoms, that compose it are arranged in an orderly, repeating, three-dimensional array. Solid materials that have no such orderly arrangement are referred to as *glassy* or *amorphous* (without form) and are not conventionally referred to as minerals. Windowpane glass is amorphous, as are some natural glasses formed during volcanic eruptions. Later in this chapter, we will explore in detail the process by which crystalline materials form.

Generally Inorganic . . . Minerals are defined as inorganic substances and so exclude the organic materials that make up plant and animal bodies. Organic matter is com-

posed of organic carbon, the form of carbon found in all organisms, living or dead. Decaying vegetation in a swamp may be geologically transformed into coal, which also is made of organic carbon; but although it is found as a natural deposit, coal is not traditionally considered a mineral. Many minerals are, however, secreted by organisms. One such mineral, calcite (**Figure 3.1**), forms the shells of oysters and many other organisms, and it contains inorganic carbon. The calcite of these shells, which constitute the bulk of many limestones, fits the definition of a mineral because it is inorganic and crystalline.

. . . With a Specific Chemical Composition The key to understanding the composition of Earth's materials lies in knowing how the chemical elements are organized into minerals. What makes each mineral unique is the combination of its chemical composition and the arrangement of its atoms in an internal structure. A mineral's chemical composition either is fixed or varies within defined limits. The mineral quartz, for example, has a fixed ratio of two atoms of oxygen to one atom of silicon. This ratio never varies, although quartz is found in many different kinds of rock. The components of the mineral olivine—iron, magnesium, and silicon—always have a fixed ratio. Although the ratio of iron to magnesium atoms may vary, the sum of those atoms in relation to the number of silicon atoms always forms a fixed ratio.



The Atomic Structure of Matter

A modern dictionary lists many meanings for the word *atom* and its derivatives. One of the first is “anything considered the smallest possible unit of any material.” To the ancient

Greeks, *atomos* meant “indivisible.” John Dalton (1766–1844), an English chemist and the father of modern atomic theory, proposed that atoms are particles of matter of several kinds that are so small that they cannot be seen with any microscope and so universal that they compose all substances. In 1805, Dalton hypothesized that each of the various chemical elements consists of a different kind of atom, that all atoms of any given element are identical, and that chemical compounds are formed by various combinations of atoms of different elements in definite proportions.

By the early twentieth century, physicists, chemists, and mineralogists, building on Dalton’s ideas, had come to understand the structure of matter much as we do today. We now know that an **atom** is the smallest unit of an element that retains the physical and chemical properties of that element. We also know that atoms are the small units of matter that combine in chemical reactions and that atoms themselves are divisible into even smaller units.

The Structure of Atoms

Understanding the structure of atoms allows us to predict how chemical elements will react with one another and form new crystal structures. For more detailed information about the structure of atoms, see Appendix 4.

The Nucleus: Protons and Neutrons At the center of every atom is a dense **nucleus** containing virtually all the mass of the atom in two kinds of particles: protons and neutrons (Figure 3.2). A **proton** has a positive electrical charge of +1. A **neutron** is electrically neutral—that is, uncharged. Atoms of the same chemical element may have different numbers of neutrons, but the number of their protons does not vary. For instance, all carbon atoms have six protons.

Electrons Surrounding the nucleus is a cloud of moving particles called **electrons**, each with a mass so small that it is conventionally taken to be zero. Each electron carries an electrical charge of -1 . The number of protons in the nucleus of any atom is balanced by the same number of electrons in the cloud surrounding the nucleus, so an atom is electrically neutral. Thus the nucleus of the carbon atom is surrounded by six electrons (see Figure 3.2).

Atomic Number and Atomic Mass

The number of protons in the nucleus of an atom is called its **atomic number**. Because all atoms of the same element have the same number of protons, they also have the same atomic number. All atoms with six protons, for example, are carbon atoms (atomic number 6). In fact, the atomic number of an element can tell us so much about an element’s behavior that the periodic table organizes elements according to their atomic number (Figure 3.3). Elements in the same vertical group, such as carbon and silicon, tend to react similarly. For more detail about the periodic table, see Appendix 4.

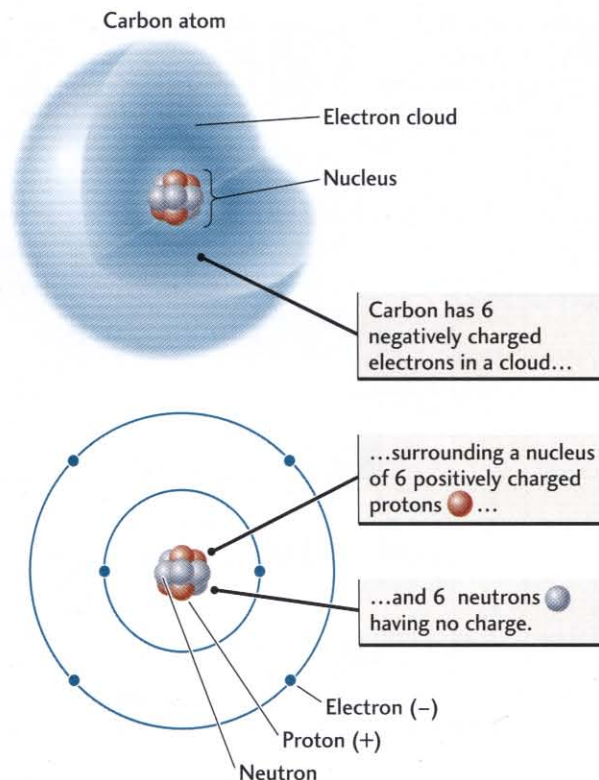


Figure 3.2 Electron structure of the carbon atom (carbon-12). The electrons, each with a charge of -1 , are represented as a negatively charged cloud surrounding the nucleus, which contains six protons, each with a charge of $+1$, and six neutrons, each with zero charge. The size of the nucleus is greatly exaggerated; it is much too small to show at a true scale.

The **atomic mass** of an element is the sum of the masses of its protons and neutrons. (Electrons, because they have so little mass, are not included in this sum.) Although the number of protons is constant, atoms of the same chemical element may have different numbers of neutrons and therefore different atomic masses. These various kinds of atoms are called **isotopes**. Isotopes of the element carbon, for example, all with six protons, exist with six, seven, and eight neutrons, giving atomic masses of 12, 13, and 14.

In nature, the chemical elements exist as mixtures of isotopes, so their atomic masses are never whole numbers. Carbon’s atomic mass, for example, is 12.011. It is close to 12 because the isotope carbon-12 is overwhelmingly abundant. The relative abundance of the different isotopes of an element on Earth is determined by processes that enhance the abundance of some isotopes over others. Carbon-12, for example, is favored by some reactions, such as photosynthesis, in which organic carbon compounds are produced from inorganic carbon compounds.

Elements of major abundance in Earth's crust
 Elements of lesser abundance but of major geologic importance

Carbon → Element name
6 → Atomic number
C → Symbol
12.011 → Atomic mass

Hydrogen 1 H 1.0079																	Helium 2 He 4.0026														
Lithium 3 Li 6.941	Beryllium 4 Be 9.0122																	Boron 5 B 10.811	Carbon 6 C 12.011	Nitrogen 7 N 14.0067	Oxygen 8 O 15.9994	Fluorine 9 F 18.9984	Neon 10 Ne 20.1797								
Sodium 11 Na 22.9898	Magnesium 12 Mg 24.3050																	Aluminum 13 Al 26.9815	Silicon 14 Si 28.0855	Phosphorus 15 P 30.9738	Sulfur 16 S 32.066	Chlorine 17 Cl 35.4527	Argon 18 Ar 39.948								
Potassium 19 K 39.0983	Calcium 20 Ca 40.078	Scandium 21 Sc 44.9559	Titanium 22 Ti 47.867	Vanadium 23 V 50.9415	Chromium 24 Cr 51.9961	Manganese 25 Mn 54.9380	Iron 26 Fe 55.845	Cobalt 27 Co 58.9332	Nickel 28 Ni 58.6934	Copper 29 Cu 63.546	Zinc 30 Zn 65.39	Gallium 31 Ga 69.723	Germanium 32 Ge 72.61	Arsenic 33 As 74.9216	Selenium 34 Se 78.96	Bromine 35 Br 79.904	Krypton 36 Kr 83.80														
Rubidium 37 Rb 85.4678	Strontium 38 Sr 87.62	Yttrium 39 Y 88.9059	Zirconium 40 Zr 91.224	Niobium 41 Nb 92.9064	Molybdenum 42 Mo 95.94	Technetium 43 Tc (97.907)	Ruthenium 44 Ru 101.07	Rhodium 45 Rh 102.9055	Palladium 46 Pd 106.42	Silver 47 Ag 107.8682	Cadmium 48 Cd 112.411	Indium 49 In 114.818	Tin 50 Sn 118.710	Antimony 51 Sb 121.760	Tellurium 52 Te 127.60	Iodine 53 I 126.9045	Xenon 54 Xe 131.29														
Cesium 55 Cs 132.9054	Barium 56 Ba 137.327	Lanthanum 57 La 138.9055	Hafnium 72 Hf 178.49	Tantalum 73 Ta 180.9479	Tungsten 74 W 183.84	Rhenium 75 Re 186.207	Osmium 76 Os 190.2	Iridium 77 Ir 192.22	Platinum 78 Pt 195.08	Gold 79 Au 196.9665	Mercury 80 Hg 200.59	Thallium 81 Tl 204.3833	Lead 82 Pb 207.2	Bismuth 83 Bi 208.9804	Polonium 84 Po (208.98)	Astatine 85 At (209.99)	Radon 86 Rn (222.02)														
Francium 87 Fr (223.02)	Radium 88 Ra (226.0254)	Actinium 89 Ac (227.0278)	Rutherfordium 104 Rf (261.11)	Dubnium 105 Db (262.11)	Seaborgium 106 Sg (263.12)	Bohrium 107 Bh (262.12)	Hassium 108 Hs (265)	Mtnerium 109 Mt (266)			Ununbium 112 Uub (277)																				
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Figure 3.3 The periodic table of elements, which organizes the elements (from left to right in a row) in order of atomic number. The table highlights the elements of particular geologic importance.



Chemical Reactions

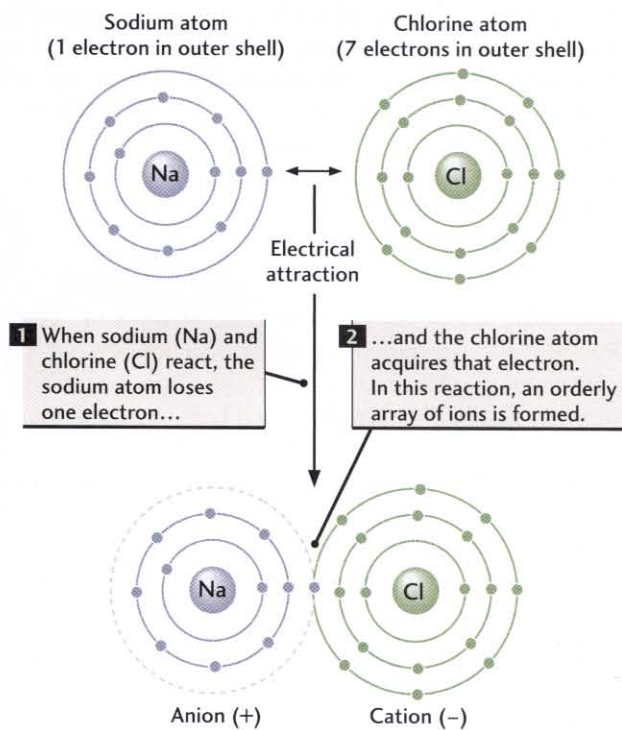
The structure of an atom determines its chemical reactions with other atoms. **Chemical reactions** are interactions of the atoms of two or more chemical elements in certain fixed proportions that produce new chemical substances—chemical compounds. For example, when two hydrogen atoms combine with one oxygen atom, they form a new chemical compound that we call water (H_2O). The properties of a chemical compound formed in the course of a reaction may be entirely different from those of its constituent elements. For example, when an atom of sodium, a metal, combines with an atom of chlorine, a noxious gas, they form the chemical compound sodium chloride, better known as table salt. We represent this compound by the chemical formula $NaCl$, the symbol Na standing for the element sodium and

the symbol Cl for the element chlorine. (Every chemical element has been assigned its own symbol, which we use as a kind of shorthand for writing chemical formulas and equations.)

Chemical compounds, such as minerals, are formed either by **electron transfer** between the reacting atoms or by **electron sharing** between the reacting atoms. In the reaction between sodium (Na) and chlorine (Cl) atoms to form sodium chloride ($NaCl$), the sodium atom loses one electron, which the chlorine atom gains (**Figure 3.4**). Because the chlorine atom has gained a negatively charged electron, it is now negatively charged, Cl^- . Likewise, the loss of an electron gives sodium a positive charge, Na^+ . The compound $NaCl$ itself remains electrically neutral because the positive charge on Na^+ is exactly balanced by the negative charge on Cl^- . A positively charged ion is called a **cation**, and a negatively charged ion is called an **anion**.



Figure 3.4 Table salt, NaCl, is formed by the reaction of chlorine and sodium atoms. [C. D. Winter/Photo Researchers.]



Atoms that do not react by gaining or losing electrons combine chemically by sharing electrons. Carbon and silicon, two of the most abundant elements in Earth's crust, tend to form compounds by electron sharing. Diamond is a compound composed entirely of carbon atoms sharing electrons (**Figure 3.5**).



Chemical Bonds

The ions or atoms of elements that make up compounds are held together by electrical forces of attraction between electrons and protons, which we call chemical bonds. The electrical attractions of shared electrons or of gained or lost

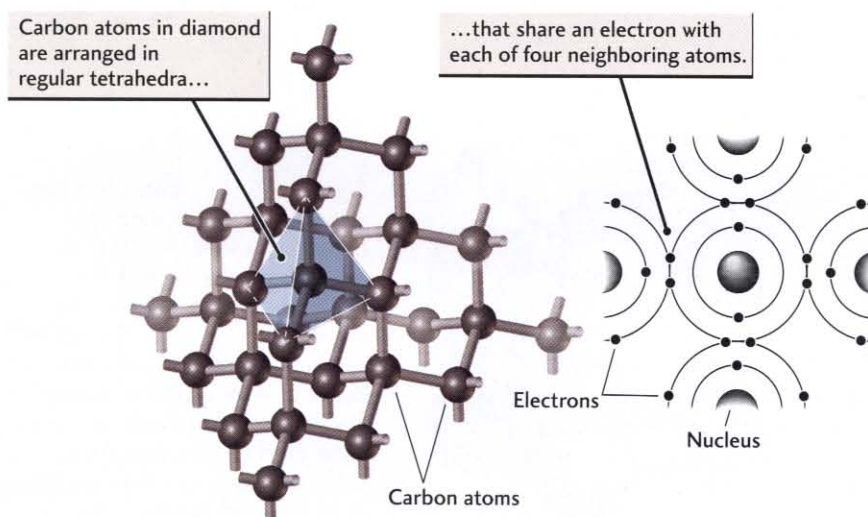


Figure 3.5 Electron sharing in diamond. The mineral diamond is composed of the single element carbon. Each carbon atom shares its four electrons with four adjacent carbon atoms.

electrons may be strong or weak, and the bonds created by these attractions are correspondingly strong or weak. Strong bonds keep a substance from chemically decomposing into its elements or into other compounds. They also make minerals hard and keep them from cracking or splitting. Two major types of bonds are found in most rock-forming minerals: ionic bonds and covalent bonds.

Ionic Bonds

The simplest form of chemical bond is the **ionic bond**. Bonds of this type form by electrical attraction between ions of the opposite charge, such as Na^+ and Cl^- in sodium chloride (see Figure 3.4). This attraction is of exactly the same nature as the static electricity that can make clothing of nylon or silk cling to the body. The strength of an ionic bond decreases greatly as the distance between ions increases. Bond strength increases as the electrical charges of the ions increase. Ionic bonds are the dominant type of chemical bonds in mineral structures; *about 90 percent of all minerals are essentially ionic compounds.*

Covalent Bonds

Elements that do not readily gain or lose electrons to form ions and instead form compounds by sharing electrons are held together by **covalent bonds**, which are generally stronger than ionic bonds. One mineral with a covalently bonded crystal structure is diamond, consisting of the single element carbon. Carbon atoms have four electrons and acquire four more by electron sharing. In diamond, every carbon atom (not an ion) is surrounded by four others arranged in a regular *tetrahedron*, a four-sided pyramidal form, each side a triangle (see Figure 3.5). In this configuration, each carbon atom shares an electron with each of its four neighbors, resulting in a very stable configuration. Figure 3.5 shows a network of carbon tetrahedra linked together.

Atoms of metallic elements, which have strong tendencies to lose electrons, pack together as cations, and the freely mobile electrons are shared and dispersed among the ions. This free electron sharing results in a kind of covalent bond

that we call a **metallic bond**. It is found in a small number of minerals, among them the metal copper and some sulfides.

The chemical bonds of some minerals are intermediate between pure ionic and pure covalent bonds because some electrons are exchanged and others are shared.

The Atomic Structure of Minerals

Minerals can be viewed in two complementary ways: as crystals (or grains) that we can see with the naked eye and as assemblages of submicroscopic atoms organized in an ordered three-dimensional array. We are now prepared for a closer look at the orderly forms that characterize mineral structure and at the conditions under which minerals form. Later in this chapter, we will see that the crystal structures of minerals are manifested in their physical properties. First, however, we turn to the question of how minerals form.

How Do Minerals Form?

Minerals form by the process of **crystallization**, the growth of a solid from a gas or liquid whose constituent atoms come together in the proper chemical proportions and crystalline arrangement. (Remember that the atoms in a mineral are arranged in an ordered three-dimensional array.) The bonding of carbon atoms in diamond, a covalently bonded mineral, is one example of crystallization and crystal structure. Carbon atoms bind together in tetrahedra, each tetrahedron attaching to another and building up a regular three-dimensional structure from a great many atoms (see Figure 3.5). As a diamond crystal grows, it extends its tetrahedral structure in all directions, always adding new atoms in the proper geometric arrangement. Diamonds can be synthesized under very high pressures and temperatures that mimic conditions in Earth's mantle.

The sodium and chloride ions that make up sodium chloride, an ionically bonded mineral, also crystallize in an orderly three-dimensional array. In **Figure 3.6a**, we can see

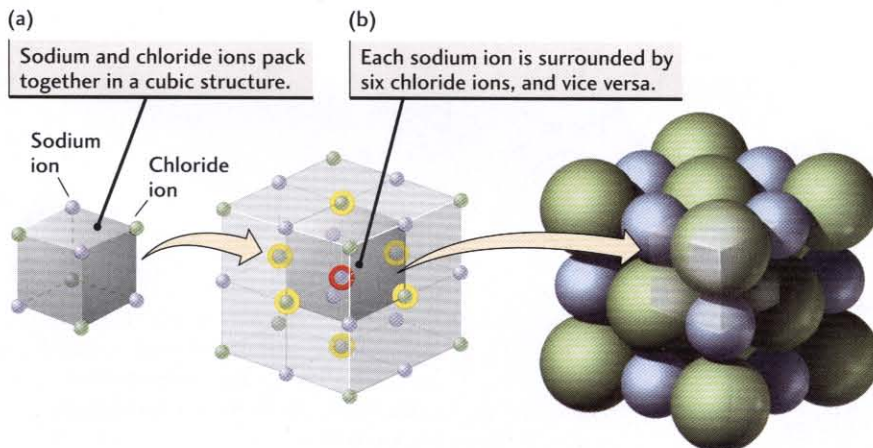


Figure 3.6 Structure of sodium chloride. (a) The dashed lines between the ions show the cubic geometry of this mineral; they do not represent bonds. Note that each sodium ion is surrounded by six chloride ions. (Ions are not drawn to scale.) (b) The relative sizes of sodium and chloride ions allow them to pack together in a cubic structure. Ions here are shown in their correct relative sizes.

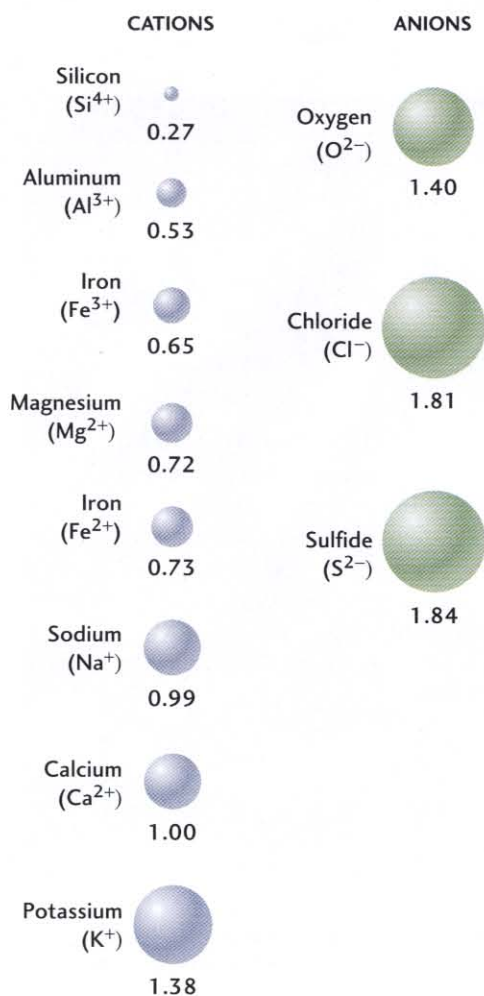


Figure 3.7 Sizes of ions as they are commonly found in rock-forming minerals. Ionic radii are given in 10^{-8} cm. [After L. G. Berry, B. Mason, and R. V. Dietrich, *Mineralogy*. San Francisco: W. H. Freeman, 1983.]

the geometry of their arrangement, with each ion of one kind surrounded by six ions of the other in a series of *cubic* structures extending in three directions. We can think of ions as if they were solid spheres, packed together in close-fitting structural units. Figure 3.6b shows the relative sizes of the ions in NaCl. There are six neighboring ions in NaCl's basic structural unit. The relative sizes of the sodium and chloride ions allow them to fit together in a closely packed arrangement.

Many of the cations of abundant minerals are relatively small; most anions are large (Figure 3.7). This is the case with the most common Earth anion, oxygen. Because anions tend to be larger than cations, it is apparent that most of the space of a crystal is occupied by the anions and that cations fit into the spaces between them. As a result, crystal structures are determined largely by how the anions are arranged and how the cations fit between them.

Cations of similar sizes and charges tend to substitute for one another and to form compounds having the same

crystal structure but differing chemical composition. *Cation substitution* is common in minerals containing the silicate ion (SiO₄⁴⁻). This process is illustrated by olivine, a silicate mineral abundant in many volcanic rocks.

Iron (Fe) and magnesium (Mg) ions are similar in size, and both have two positive charges, so they easily substitute for each other in the structure of olivine. The composition of pure magnesium olivine is Mg₂SiO₄; the pure iron olivine is Fe₂SiO₄. The composition of olivine with both iron and magnesium is given by the formula (Mg,Fe)₂SiO₄, which simply means that the number of iron and magnesium cations may vary, but their combined total (expressed as a subscript 2) does not vary in relation to each SiO₄⁴⁻ ion. The proportion of iron to magnesium is determined by the relative abundance of the two elements in the molten material from which the olivine crystallized. In many silicate minerals, aluminum (Al) substitutes for silicon (Si). Aluminum and silicon ions are so similar in size that aluminum can take the place of silicon in many crystal structures. The difference in charge between aluminum (3+) and silicon (4+) ions is balanced by an increase in the number of other cations, such as sodium (1+).

Crystallization starts with the formation of microscopic single **crystals**, ordered three-dimensional arrays of atoms in which the basic arrangement is repeated in all directions. The boundaries of crystals are natural flat (plane) surfaces called *crystal faces*. The crystal faces of a mineral are the external expression of the mineral's internal atomic structure. **Figure 3.8** pairs drawings of perfect crystals (which

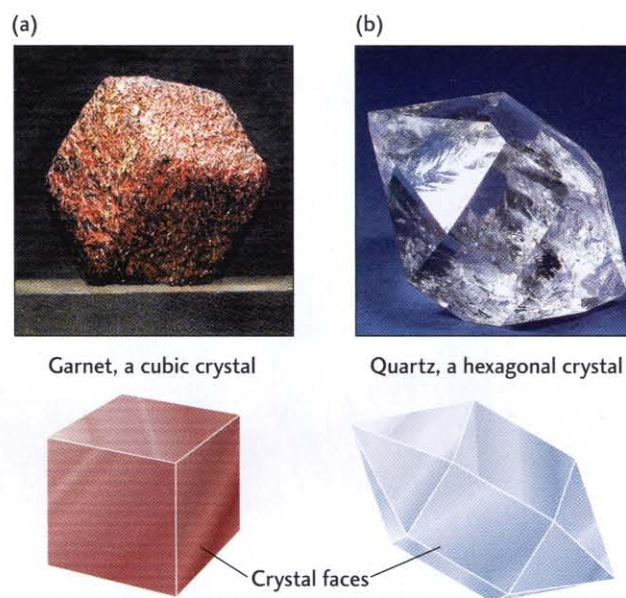


Figure 3.8 Perfect crystals. A perfect crystal is rare, but no matter how irregular the shapes of the faces may be, the angles are always exactly the same. [(a) Andrew Romeo-coolrox.com; (b) Breck P. Kent.]

are very rare in nature) with photographs of two actual minerals. The simple geometric cubes of garnet crystals correspond to the cubic arrangement of its ions. The six-sided (hexagonal) shape of the quartz crystal corresponds to its hexagonal internal atomic structure.

During crystallization, the initially microscopic crystals grow larger, maintaining their crystal faces as long as they are free to grow. Large crystals with well-defined faces form when growth is slow and steady and space is adequate to allow growth without interference from other crystals nearby. For this reason, most large mineral crystals form in open spaces in rocks, such as fractures or cavities (Figure 3.9).

Often, however, the spaces between growing crystals fill in, or crystallization proceeds too rapidly. Crystals then grow over one another and coalesce to become a solid mass of crystalline particles, or *grains*. In this case, few or no grains show crystal faces (see Figure 3.9). Large crystals that can be seen with the naked eye are relatively unusual, but many microscopic minerals in rocks display crystal faces.

Unlike crystalline minerals, glassy materials—which solidify from liquids so quickly that they lack any internal atomic order—do not form crystals with plane faces. Instead they are found as masses with curved, irregular surfaces. The most common glass is volcanic glass.

When Do Minerals Form?

Lowering the temperature of a liquid below its freezing point is one way to start the process of crystallization. In water, for example, 0°C is the temperature below which crystals of ice, a mineral, start to form. Similarly, a mag-



Figure 3.9 This sample of amethyst crystals displays large, well-formed crystals. [José Manuel Sanchis Calvete/Corbis.]



Figure 3.10 A halite deposit from the Sultanate of Oman. This deposit, which is more than 500 million years old, is preserved in a drill core from the deep subsurface. The black band is concentrated organic matter derived from microorganisms that lived in extreme hypersaline environments that formed when the ancient ocean dried up. [John Grotzinger.]

ma—a hot, molten liquid rock—crystallizes solid minerals when it cools. As a magma falls below its melting point, which may be higher than 1000°C, crystals of silicate minerals such as olivine or feldspar begin to form. (Geologists usually refer to melting points of magmas rather than freezing points, because freezing normally implies cold.)

Another set of conditions that can produce crystallization occurs as liquids evaporate from a solution. A solution is formed when one chemical substance is dissolved in another, such as salt in water. As the water evaporates from a salt solution, the concentration of salt eventually gets so high that the solution is said to be saturated—it can hold no more salt. If evaporation continues, the salt starts to **precipitate**, or drop out of solution as crystals. Deposits of halite or table salt form under just these conditions when seawater evaporates to the point of saturation in some hot, arid bays or arms of the ocean (Figure 3.10).

Diamond and graphite exemplify the dramatic effects that temperature and pressure can have on mineral formation. Diamond and graphite (the material that is used as the “lead” in pencils) are **polymorphs**, alternative structures for a single chemical compound (Figure Story 3.11). These

CARBON AND SILICON EXIST AS POLYMORPHIC MINERALS

CARBON POLYMORPH MINERALS

(a) Graphite

1 Polymorphs are alternative structures of a single chemical compound, in this case carbon.

2 Graphite is formed at lower pressures and temperatures than diamond.

3 Its carbon forms sheets whose atoms are more loosely packed than those in diamond.

Graphite

(b) Diamond

4 Natural diamond is formed by very high pressures and temperatures in Earth's mantle.

5 Its carbon atoms are closely packed.

Diamond

SILICATE AND SILICATE POLYMORPH MINERALS

(c) Silicate ion (SiO_4^{4-})

Silicon ion (Si^{4+})

Oxygen ions (O^{2-})

6 The silicate ion forms tetrahedra with a central silicon ion surrounded by four oxygen ions.

Quartz structure

7 Quartz is made of silicate tetrahedra arranged in the same way as the tetrahedra in diamond.

(d) Isolated tetrahedra (e) Single chains (f) Double chains (g) Sheet (h) Framework

8 Tetrahedra arranged in other ways are characteristic of other silicate minerals.

Olivine

Pyroxene

Amphibole

Muscovite

Feldspar

Figure Story 3.11 Polymorphs of carbon and silicate. [Graphite: John A. Jaszczak, Michigan Technological University. Diamond: Charles O'Rear/Corbis. Olivine: Chip Clark. Pyroxene: Chip Clark. Amphibole (hornblende): George Whiteley/Photo Researchers. Muscovite (mica): Chip Clark. Feldspar: Chip Clark.]

two minerals, both formed from carbon, have different crystal structures and very different appearances (Figure Story 3.11a and 11b). From experimentation and geological observation, we know that diamond forms and remains stable at the very high pressures and temperatures of Earth's mantle. The high pressure in the mantle forces the atoms in diamond to be closely packed. Diamond therefore has a higher density (mass per unit volume), 3.5 g/cm^3 , than graphite, which is less closely packed and has a density of only 2.1 g/cm^3 . Graphite forms and is stable at relatively moderate pressures and temperatures, such as those in Earth's crust.

Low temperatures also can produce closer packing. Quartz and cristobalite are polymorphs of silica (SiO_2). Quartz forms at low temperatures and is relatively dense (2.7 g/cm^3). Cristobalite, which forms at a higher temperature, has a more open structure and is therefore less dense (2.3 g/cm^3).



Rock-Forming Minerals

All minerals have been grouped into eight classes according to their chemical composition; six of those classes are listed in Table 3.1. Some minerals, such as copper, occur naturally as un-ionized pure elements, and they are classified as *native elements*. Most others are classified by their anions. Olivine, for example, is classed as a silicate by its silicate anion, SiO_4^{4-} . Halite (NaCl) is classed as a halide by its chloride anion, Cl^- . So is its close relative sylvite, potassium chloride (KCl).

Although many thousands of minerals are known, geologists commonly encounter only about 30 of them. These minerals are the building blocks of most crustal rocks, and so they are called *rock-forming minerals*. Their relatively

small number corresponds to the small number of elements that are found in major abundance in Earth's crust. As we learned in Chapter 1, 99 percent of the crust is made up of only nine elements.

In the following pages, we consider the most common rock-forming minerals:

- *Silicates*, the most abundant minerals in Earth's crust, are composed of oxygen (O) and silicon (Si)—the two most abundant elements in the crust—mostly in combination with the cations of other elements.
- *Carbonates* are minerals made of carbon and oxygen in the form of the carbonate anion (CO_3^{2-}) in combination with calcium and magnesium. Calcite (CaCO_3) is one such mineral.
- *Oxides* are compounds of the oxygen anion (O^{2-}) and metallic cations; an example is the mineral hematite (Fe_2O_3).
- *Sulfides* are compounds of the sulfide anion (S^{2-}) and metallic cations, a group that includes the mineral pyrite (FeS_2).
- *Sulfates* are compounds of the sulfate anion (SO_4^{2-}) and metallic cations, a group that includes the mineral anhydrite (CaSO_4).

The other chemical classes of minerals, including native elements and halides, are not as common as the rock-forming minerals.

Silicates

The basic building block of all silicate mineral structures is the *silicate ion*. It is a tetrahedron—a pyramidal structure with four sides—composed of a central silicon ion (Si^{4+}) surrounded by four oxygen ions (O^{2-}), giving the formula

Table 3.1 Some Chemical Classes of Minerals

Class	Defining Anions	Example
Native elements	None: no charged ions	Copper metal (Cu)
Oxides and hydroxides	Oxygen ion (O^{2-}) Hydroxyl ion (OH^-)	Hematite (Fe_2O_3) Brucite ($\text{Mg}[\text{OH}]_2$)
Halides	Chloride (Cl^-), fluoride (F^-), bromide (Br^-), iodide (I^-)	Halite (NaCl)
Carbonates	Carbonate ion (CO_3^{2-})	Calcite (CaCO_3)
Sulfates	Sulfate ion (SO_4^{2-})	Anhydrite (CaSO_4)
Silicates	Silicate ion (SiO_4^{4-})	Olivine (Mg_2SiO_4)

SiO_4^{4-} (Figure Story 3.11c). Because the silicate ion has a negative charge, it often bonds to cations to form electrically neutral minerals. The silicate ion typically bonds with cations such as sodium (Na^+), potassium (K^+), calcium (Ca^+), magnesium (Mg^{2+}), and iron (Fe^{2+}). Alternatively, it can share oxygen ions with other silicon-oxygen tetrahedra. Tetrahedra may be isolated (linked only to cations), or they may be linked to other silica tetrahedra in rings, single chains, double chains, sheets, or frameworks, some of which are shown in Figure Story 3.11.

Isolated Tetrahedra Isolated tetrahedra are linked by the bonding of each oxygen ion of the tetrahedron to a cation (Figure Story 3.11d). The cations, in turn, bond to the oxygen ions of other tetrahedra. The tetrahedra are thus isolated from one another by cations on all sides. Olivine is a rock-forming mineral with this structure.

Single-Chain Linkages Single chains also form by sharing oxygen ions. Two oxygen ions of each tetrahedron bond to adjacent tetrahedra in an open-ended chain (Figure Story 3.11e). Single chains are linked to other chains by cations. Minerals of the pyroxene group are single-chain silicate minerals. Enstatite, a pyroxene, is composed of iron or magnesium ions, or both, and is limited to a chain of tetrahedra in which the two cations may substitute for each other, as in olivine. The formula $(\text{Mg,Fe})\text{SiO}_3$ represents this structure.

Double-Chain Linkages Two single chains may combine to form double chains linked to each other by shared oxygen ions (Figure Story 3.11f). Adjacent double chains linked by cations form the structure of the amphibole group of minerals. Hornblende, a member of this group, is an extremely common mineral in both igneous and metamorphic rocks. It has a complex composition that includes calcium (Ca^{2+}), sodium (Na^+), magnesium (Mg^{2+}), iron (Fe^{2+}), and aluminum (Al^{3+}).

Sheet Linkages In sheet structures, each tetrahedron shares three of its oxygen ions with adjacent tetrahedra to build stacked sheets of tetrahedra (Figure Story 3.11g). Cations

may be interlayered with tetrahedral sheets. The micas and clay minerals are the most abundant sheet silicates. Muscovite, $\text{KA}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$, is one of the most common sheet silicates and is found in many types of rocks. It can be separated into extremely thin, transparent sheets. Kaolinite, $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$, which also has this structure, is a common clay mineral found in sediments and is the basic raw material for pottery.

Frameworks Three-dimensional frameworks form as each tetrahedron shares all its oxygen ions with other tetrahedra. Feldspars, the most abundant minerals in Earth's crust, are framework silicates (Figure Story 3.11h), as is another of the most common minerals, quartz (SiO_2).

Silicate Compositions Chemically, the simplest silicate is silicon dioxide, also called silica (SiO_2), which is found most often as the mineral quartz. When the silicate tetrahedra of quartz are linked, sharing two oxygen ions for each silicon ion, the total formula adds up to SiO_2 .

In other silicate minerals, the basic units—rings, chains, sheets, and frameworks—are bonded to such cations as sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), and iron (Fe^{2+}). As noted in the discussion of cation substitution, aluminum (Al^{3+}) substitutes for silicon in many silicate minerals.

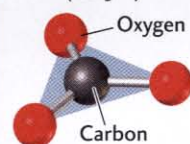
Carbonates

The nonsilicate mineral calcite (calcium carbonate, CaCO_3) is one of the abundant minerals in Earth's crust and is the chief constituent of a group of rocks called limestones (Figure 3.12). Its basic building block, the carbonate ion (CO_3^{2-}), consists of a carbon ion surrounded by three oxygen ions in a triangle, as shown in Figure 3.12b. The carbon atom shares electrons with the oxygen atoms. Groups of carbonate ions are arranged in sheets somewhat like the sheet silicates and are bonded by layers of cations (Figure 3.12c). The sheets of carbonate ions in calcite are separated by layers of calcium ions. The mineral dolomite,

(a) Limestone



(b) Carbonate ion (CO_3^{2-})



(c) Calcium carbonate structure

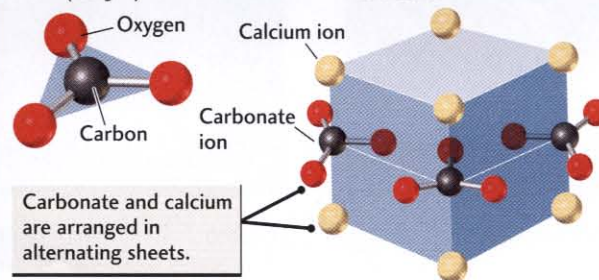


Figure 3.12 Carbonate minerals, such as calcite (calcium carbonate, CaCO_3), have a layered structure. (a) Limestone. [Leonard Lessin/Peter Arnold, Inc.] (b) Top view of the carbonate building block, a carbon ion surrounded in a triangle by three oxygen ions, with a net charge of -2 . (c) View of the alternating layers of calcium and carbonate ions.



Figure 3.13 Nonsilicate minerals: (left) hematite, (right) spinel. [Chip Clark.]

$\text{CaMg}(\text{CO}_3)_2$, another major mineral of crustal rocks, is made up of the same carbonate sheets separated by alternating layers of calcium ions and magnesium ions.

Oxides

Oxide minerals are compounds in which oxygen is bonded to atoms or cations of other elements, usually metallic ions such as iron (Fe^{2+} or Fe^{3+}). Most oxide minerals are ionically bonded, their structures varying with the size of the metallic cations. This group is of great economic importance because it includes the ores of most of the metals, such as chromium and titanium, used in the industrial and technological manufacture of metallic materials and devices. Hematite (Fe_2O_3), shown in **Figure 3.13**, is a chief ore of iron.

Another of the abundant minerals in this group, spinel, is an oxide of two metals, magnesium and aluminum (MgAl_2O_4). Spinel (**Figure 3.13**) has a closely packed cubic structure and a high density (3.6 g/cm^3), reflecting the conditions of high pressure and temperature under which

it forms. Transparent, gem-quality spinel resembles ruby and sapphire and is found in the crown jewels of England and Russia.

Sulfides

The chief ores of many valuable minerals—such as copper, zinc, and nickel—are members of the sulfide group. This group includes compounds of the sulfide ion (S^{2-}) with metallic cations. In the sulfide ion, a sulfur atom has gained two electrons in its outer shell. Most sulfide minerals look like metals, and almost all are opaque. The most common sulfide mineral is pyrite (FeS_2), often called “fool’s gold” because of its goldish metallic appearance (**Figure 3.14**).

Sulfates

The basic building block of all sulfates is the sulfate ion (SO_4^{2-}). It is a tetrahedron made up of a central sulfur atom surrounded by four oxygen ions (O^{2-}). One of the most abundant minerals of this group is gypsum, the primary component of plaster (**Figure 3.15**). Gypsum forms when seawater evaporates. During evaporation, Ca^{2+} and SO_4^{2-} , two ions that are abundant in seawater, combine and precipitate as layers of sediment, forming calcium sulfate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). (The dot in this formula signifies that two water molecules are bonded to the calcium and sulfate ions.)

Another calcium sulfate, anhydrite (CaSO_4), differs from gypsum in that it contains no water. Its name is derived from the word *anhydrous*, meaning “free from water.” Gypsum is stable at the low temperatures and pressures found at Earth’s surface, whereas anhydrite is stable at the higher temperatures and pressures where sedimentary rocks are buried.



Figure 3.14 A sample of pyrite, also known as “fool’s gold.” [Lester V. Bergman/Corbis.]



Figure 3.15 Gypsum is a sulfate formed when seawater evaporates. [José Manuel Sanchis Calvete/Corbis.]



Physical Properties of Minerals

Geologists use their knowledge of mineral composition and structure to understand the origins of rocks. First, they must identify the minerals that compose a rock. To do so, they rely greatly on chemical and physical properties that can be observed relatively easily. In the nineteenth and early twentieth centuries, geologists carried field kits for the rough chemical analysis of minerals that would help in identification. One such test is the origin of the phrase “the acid test.” It consists of dropping diluted hydrochloric acid (HCl) on a mineral to see if it “fizzes” (Figure 3.16). The fizzing indicates that carbon dioxide (CO₂) is escaping, which means that the mineral is likely to be calcite, a carbonate mineral.

In the rest of this chapter, we will review the physical properties of minerals, many of which contribute to their practical and decorative value (see Feature 3.1).

Hardness

Hardness is a measure of the ease with which the surface of a mineral can be scratched. Just as a diamond, the hardest mineral known, scratches glass, so a quartz crystal, which is harder than feldspar, scratches a feldspar crystal. In 1822, Friedrich Mohs, an Austrian mineralogist, devised a scale (now known as the **Mohs scale of hardness**) based on the ability of one mineral to scratch another. At one extreme is the softest mineral (talc); at the other, the hardest (diamond) (Table 3.2). The Mohs scale is still one of the best practical tools for identifying an unknown mineral. With a knife blade and a few of the minerals on the hardness scale, a field geologist can gauge an unknown mineral’s position

Table 3.2 Mohs Scale of Hardness

Mineral	Scale Number	Common Objects
Talc	1	
Gypsum	2	——— Fingernail
Calcite	3	——— Copper coin
Fluorite	4	
Apatite	5	——— Knife blade
Orthoclase	6	——— Window glass
Quartz	7	——— Steel file
Topaz	8	
Corundum	9	
Diamond	10	

on the scale. If the unknown mineral is scratched by a piece of quartz but not by the knife, for example, it lies between 5 and 7 on the scale.

Recall that covalent bonds are generally stronger than ionic bonds. The hardness of any mineral depends on the strength of its chemical bonds: the stronger the bonds, the harder the mineral. Crystal structure varies in the silicate group of minerals, and so does hardness. For example, hardness varies from 1 in talc, a sheet silicate, to 8 in topaz, a silicate with isolated tetrahedra. Most silicates fall in the 5 to 7 range on the Mohs scale. Only sheet silicates are relatively soft, with hardnesses between 1 and 3.

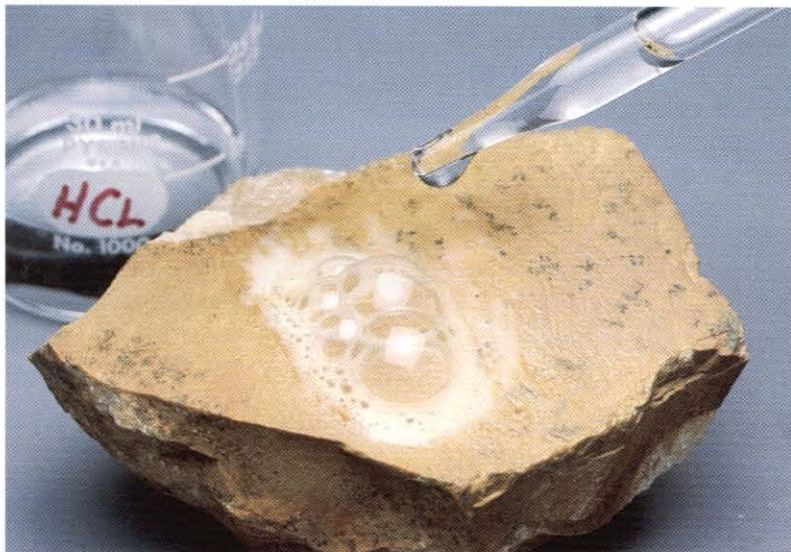


Figure 3.16 The acid test. One easy but effective way to identify certain minerals is to drop diluted hydrochloric acid (HCl) on the substance. If it fizzes, indicating the escape of carbon dioxide, the mineral is likely to be calcite. [Chip Clark.]



EARTH ISSUES

3.1 What Makes Gems So Special?

No one can be sure when the first human picked up a mineral crystal and kept it for its rare beauty, but we do know that gems were being worn as necklaces and other adornments at the dawn of civilization in Egypt, at least 4000 years ago. These early Egyptians were undoubtedly attracted to the color and play of light on the polished surfaces of such minerals as carnelian, lapis lazuli, and turquoise. Color and luster (the ability to reflect light) are two qualities that still serve to define gemstones. Although the value placed on a gemstone varies in different cultures and historical periods, other required qualities seem to be beauty, transparency, brilliance, durability, and rarity. Most minerals have some of these remarkable qualities, but the stones considered most precious are ruby; sapphire; emerald; and, of course, diamond.

A diamond—geologically speaking, at least—may not be forever, as the advertisers claim, but it is special. Its glitter is unique, as are the play of colors and the sparkle that it emits. The source of these qualities is the way in which diamond refracts, or bends, light. These characteristics are enhanced by diamond's remarkable ability to split perfectly along certain directions of the crystal, which diamond cutters use to advantage in carefully cutting gem-quality stones. Diamond's multiple facets (faces superficially similar to crystal faces) can be polished to enhance this sparkle. These facets can be ground only by other diamonds, because diamond is the hardest mineral known—so hard that it can scratch any other mineral and remain undamaged. This mineral's tightly packed crystal structure and strong covalent bonds between carbon atoms give it these characteristics, which allow it to be identified with certainty by mineralogists and jewelers.

Rubies and sapphires are gem-quality varieties of the common mineral corundum (aluminum oxide), which is widespread and abundant in a number of rock types. Although not as hard as diamond, corundum is extremely

hard. Small amounts of impurities produce the intense colors that we value. Ruby, for example, is red because of small amounts of chromium, the same substance that gives emeralds their green color.

Less valuable, sometimes called semiprecious, gemstones are topaz, garnet, tourmaline, jade, turquoise, and zircon. Most, like garnet, are common constituents of rocks, occurring mostly as small imperfect crystals with many impurities and poor transparency. But, under special conditions, gem-quality garnets form. From time to time, some minerals that are not ordinarily considered gems may enjoy sudden—perhaps temporary—popularity. Hematite (iron oxide) currently enjoys this status, appearing in necklaces and bracelets.



Sapphire (blue) and diamond (colorless) brooch by Fortunato Pio Castellani, Smithsonian Institution, nineteenth century. [Aldo Tutino/Art Resource.]

Within groups of minerals having similar crystal structures, increasing hardness is related to other factors that also increase bond strength:

- *Size*: The smaller the atoms or ions, the smaller the distance between them, the greater the electrical attraction, and thus the stronger the bond.
- *Charge*: The larger the charge of ions, the greater the attraction between ions and thus the stronger the bond.

- *Packing of atoms or ions*: The closer the packing of atoms or ions, the smaller the distance between them and thus the stronger the bond.

Size is an especially important factor for most metallic oxides and for most sulfides of metals with high atomic numbers—such as gold, silver, copper, and lead. Minerals of these groups are soft, with hardnesses of less than 3, because their metallic cations are so large. Carbonates and sulfates, groups

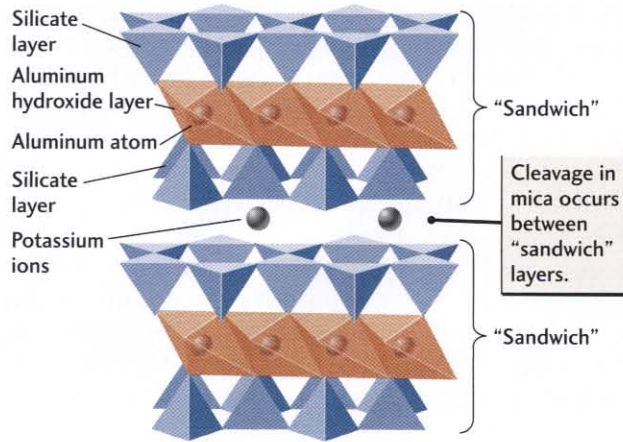


Figure 3.17 Cleavage of mica. The diagram shows the cleavage planes in the mineral structure, oriented perpendicular to the plane of the page. Horizontal lines mark the interfaces of silica-oxygen tetrahedral sheets and sheets of aluminum hydroxide



bonding the two tetrahedral layers into a "sandwich." Cleavage takes place between composite tetrahedral–aluminum hydroxide sandwiches. The photograph shows thin sheets separating along the cleavage planes. [Chip Clark.]

in which the structures are packed less densely, also are soft, with hardnesses of less than 5. In all these groups, the hardness reflects the strength of the chemical bonds.

Cleavage

Cleavage is the tendency of a crystal to break along flat planar surfaces. The term is also used to describe the geometric pattern produced by such breakage. Cleavage varies inversely with bond strength: high bond strength produces poor cleavage; low bond strength produces good cleavage. Because of their strength, covalent bonds generally give poor or no cleavage. Ionic bonds are relatively weak, so they give excellent cleavage.

If the bonds between some of the planes of atoms or ions in a crystal are weak, the mineral can be made to split along those planes. Muscovite, a mica sheet silicate, breaks along smooth, lustrous, flat, parallel surfaces, forming transparent sheets less than a millimeter thick. Mica's excellent cleavage results from weakness of the bonds between the sandwiched layers of cations and tetrahedral silica sheets (**Figure 3.17**).

Cleavage is classified according to two primary sets of characteristics: (1) the number of planes and pattern of cleavage, and (2) the quality of surfaces and ease of cleaving.

Number of Planes; Pattern of Cleavage The number of planes and patterns of cleavage are identifying hallmarks of many rock-forming minerals. Muscovite, for example, has only one plane of cleavage, whereas calcite and dolomite have three excellent cleavage directions that give them a rhomboidal shape (**Figure 3.18**).

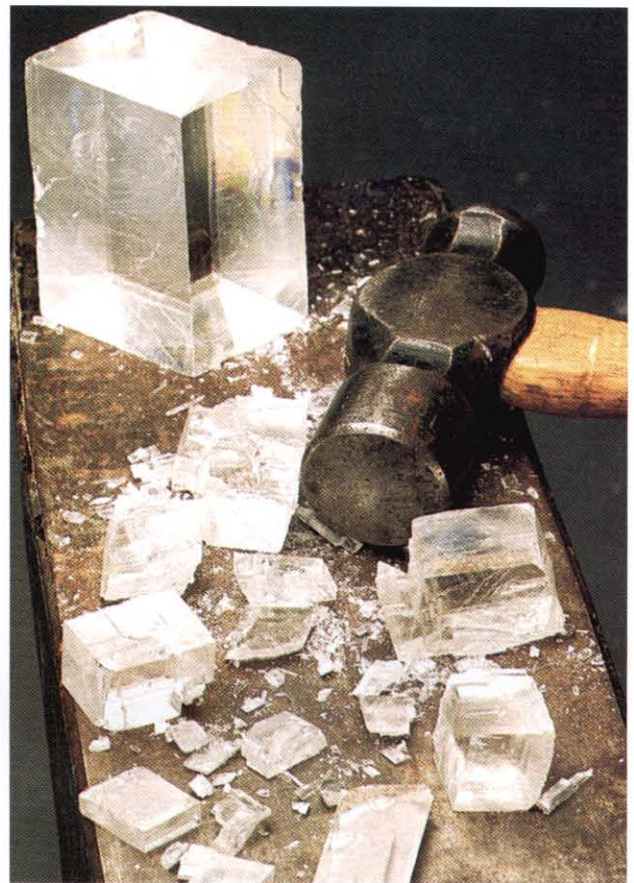


Figure 3.18 Example of rhomboidal cleavage in calcite. Calcite can be cleaved by a light hammer blow on a chisel oriented parallel to one of its planes. [Chip Clark.]

A crystal's structure determines its cleavage planes and its crystal faces. Crystals have fewer cleavage planes than possible crystal faces. Faces may be formed along any of numerous planes defined by rows of atoms or ions. Cleavage occurs along any of those planes across which the bonding is weak. All crystals of a mineral exhibit its characteristic cleavage, whereas only some crystals display particular faces.

Galena (lead sulfide, PbS) and halite (sodium chloride, NaCl) cleave along three planes, forming perfect cubes. Distinctive angles of cleavage help identify two important groups of silicates, the pyroxenes and amphiboles, that otherwise often look alike (Figure 3.19). Pyroxenes have a single-chain linkage and are bonded so that their cleavage planes are almost at right angles (about 90°) to each other. In cross section, the cleavage pattern of pyroxene is nearly a square. In contrast, amphiboles, the double chains, bond to give two cleavage planes, at about 60° and 120° to each other. They produce a diamond-shaped cross section.

Quality of Surfaces; Ease of Cleaving A mineral's cleavage is assessed as perfect, good, or fair, according to the quality of surfaces produced and the ease of cleaving. Muscovite can be cleaved easily, producing extremely high quality, smooth surfaces; its cleavage is *perfect*. The single- and double-chain silicates (pyroxenes and amphiboles, respectively) show *good* cleavage. Although these minerals

break easily along the cleavage plane, they also break across it, producing cleavage surfaces that are not as smooth as those of mica. *Fair* cleavage is shown by the ring silicate beryl. Beryl's cleavage is less regular, and the mineral breaks relatively easily along directions other than cleavage planes.

Many minerals are so strongly bonded that they lack even fair cleavage. Quartz, a framework silicate, is so strongly bonded in all directions that it breaks only along irregular surfaces. Garnet, an isolated tetrahedral silicate, also is bonded strongly in all directions and so has no cleavage. This absence of a tendency to cleave is found in most framework silicates and in silicates with isolated tetrahedra.

Fracture

Fracture is the tendency of a crystal to break along irregular surfaces other than cleavage planes. All minerals show fracture, either across cleavage planes or—in minerals such as quartz, with no cleavage—in any direction. Fracture is related to how bond strengths are distributed in directions that cut across crystal planes. Breakage of these bonds results in irregular fractures. Fractures may be *conchoidal*, showing smooth, curved surfaces like those of a thick piece of broken glass. A common fracture surface with an appearance like split wood is described as *fibrous* or *splintery*. The shape and appearance of many kinds of irregular fractures depend on the particular structure and composition of the mineral.

Luster

The way in which the surface of a mineral reflects light gives it a characteristic **luster**. Mineral lusters are described by the terms listed in Table 3.3. Luster is controlled by the kinds of atoms present and their bonding, both of which affect the way light passes through or is reflected by the mineral. Ionically bonded crystals tend to be glassy, or vitreous, but covalently bonded materials are more variable. Many tend to have an adamantine luster, like that of diamond. Metallic luster is shown by pure metals, such as gold, and by many sulfides, such as galena (lead sulfide, PbS). Pearly luster results from multiple reflections of light from planes beneath the surfaces of translucent minerals, such as the mother-of-pearl inner surfaces of many clam shells, which are made of the mineral aragonite. Luster, although an important criterion for field classification, depends heavily on the visual perception of reflected light. Textbook descriptions fall short of the actual experience of holding the mineral in your hand.

Color

The **color** of a mineral is imparted by light—either transmitted through or reflected by crystals, irregular masses, or a streak. **Streak** refers to the color of the fine deposit of mineral dust left on an abrasive surface, such as a tile of

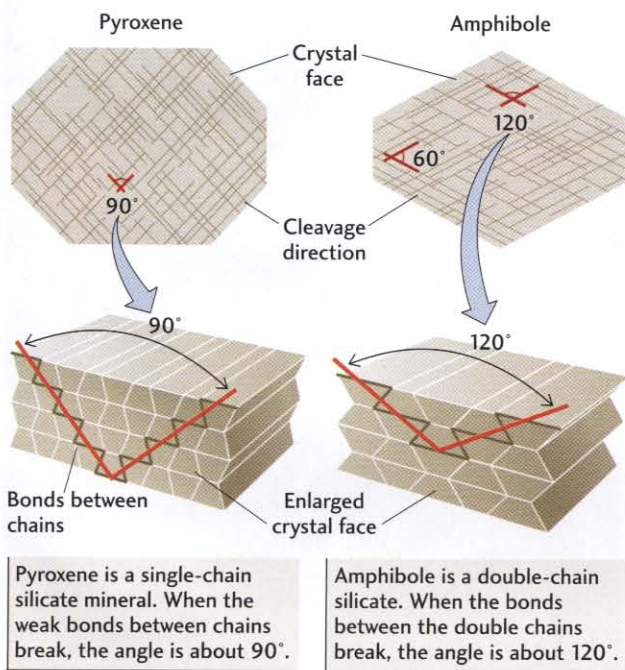


Figure 3.19 Comparison of cleavage directions and typical crystal faces in pyroxene and amphibole. These two minerals often look very much alike, but their angles of cleavage differ. These angles are frequently used to identify and classify them.

Table 3.3 Mineral Luster

Luster	Characteristics
Metallic	Strong reflections produced by opaque substances
Vitreous	Bright, as in glass
Resinous	Characteristic of resins, such as amber
Greasy	The appearance of being coated with an oily substance
Pearly	The whitish iridescence of such materials as pearl
Silky	The sheen of fibrous materials such as silk
Adamantine	The brilliant luster of diamond and similar minerals

unglazed porcelain, when a mineral is scraped across it. Such tiles are called *streak plates* (Figure 3.20). A streak plate is a good diagnostic tool because the uniform small grains of mineral that are present in the powder on the ceramic tile permit a better analysis of color than does a mass of the mineral. A mass formed of hematite (Fe_2O_3), for example, may be black, red, or brown, but this mineral will always leave a trail of reddish brown dust on a streak plate.



Figure 3.20 Hematite may be black, red, or brown, but it always leaves a reddish brown streak when scratched along a ceramic plate. [Breck P. Kent.]

Color is a complex and not yet fully understood property of minerals. It is determined both by the kinds of ions found in the pure mineral and by trace impurities.

Ions and Mineral Color The color of pure substances depends on the presence of certain ions, such as iron or chromium, that strongly absorb portions of the light spectrum. Olivine that contains iron, for example, absorbs all colors except green, which it reflects, so we see this type of olivine as green. We see pure magnesium olivine as white (transparent and colorless).

Trace Impurities and Mineral Color All minerals contain impurities. Instruments can now measure even very small quantities of some elements—as little as a billionth of a gram in some cases. Elements that make up much less than 0.1 percent of a mineral are reported as “traces,” and many of them are called trace elements.

Some trace elements can be used to interpret the origins of the minerals in which they are found. Others, such as the trace amounts of uranium in some granites, contribute to local natural radioactivity. Still others, such as small dispersed flakes of hematite that color a feldspar crystal brownish or reddish, are notable because they give a general color to an otherwise colorless mineral. Many of the gem varieties of minerals, such as emerald (green beryl) and sapphire (blue corundum), get their color from trace impurities dissolved in the solid crystal (see Feature 3.1). Emerald derives its color from chromium; the source of sapphire’s blue color is iron and titanium.

The color of a mineral may be distinctive, but it is not the most reliable clue to its identity. Some minerals always show the same color; others may have a range of colors. Many minerals show a characteristic color only on freshly broken surfaces or only on weathered surfaces. Some—precious opals, for example—show a stunning display of colors on reflecting surfaces. Others change color slightly with a change in the angle of the light shining on their surfaces.

Specific Gravity and Density

One can easily feel the difference in weight between a piece of hematite iron ore and a piece of sulfur of the same size by hefting the two pieces. A great many common rock-forming minerals, however, are too similar in **density**—mass per unit volume (usually expressed in grams per cubic centimeter, g/cm^3)—for such a simple test. Scientists therefore need some easy method for measuring this property of minerals. A standard measure of density is **specific gravity**, which is the weight of a mineral in air divided by the weight of an equal volume of pure water at 4°C .

Density depends on the atomic mass of a mineral’s ions and the closeness with which they are packed in its crystal structure. Consider the iron oxide magnetite, with a density of $5.2 \text{ g}/\text{cm}^3$. This high density results partly from the high

atomic mass of iron and partly from the closely packed structure that magnetite has in common with the other members of the spinel group of minerals (see page 62). The density of the iron silicate olivine, 4.4 g/cm^3 , is lower than that of magnetite for two reasons. First, the atomic mass of silicon, one of the elements from which olivine is formed, is lower than that of iron. Second, this olivine has a more openly packed structure than do minerals of the spinel group. The density of magnesium olivine is even lower, 3.32 g/cm^3 , because magnesium's atomic mass is much lower than that of iron. Increases in density caused by increases in pressure affect the way that minerals transmit light, heat, and earthquake waves. Experiments at extremely high pressures have shown that olivine converts into the denser structure of the spinel group at pressures corresponding to a depth of 400 km. At a greater depth, 670 km, mantle materials are further transformed into silicate minerals with the even more densely packed structure of the mineral perovskite (calcium titanate, CaTiO_3). Because of the huge volume of the lower mantle, perovskite is probably the most abundant mineral in the Earth as a whole. Some perovskite minerals have been synthesized to be high-temperature semiconductors, which conduct electricity without loss of current and may have large commercial potential. Mineralogists experienced with natural perovskites helped unravel the structure of these newly created materials. Temperature also affects density: the higher the temperature, the more open and expanded the structure and thus the lower the density.

Crystal Habit

A mineral's **crystal habit** is the shape in which its individual crystals or aggregates of crystals grow. Crystal habits are often named after common geometric shapes, such as blades, plates, and needles. Some minerals have such a distinctive crystal habit that they are easily recognizable. An example is quartz, with its six-sided column topped by a pyramid-like set of faces. These shapes indicate not only the planes of atoms or ions in the mineral's crystal structure but also the typical speed and direction of crystal growth. Thus, a needlelike crystal is one that grows very quickly in one direction and very slowly in all other directions. In contrast, a plate-shaped crystal (often referred to as *platy*) grows fast in all directions that are perpendicular to its single direction of slow growth. Fibrous crystals take shape as multiple long, narrow fibers, essentially aggregates of long needles. *Asbestos* is a generic name for a group of silicates with a more or less fibrous habit that allows the crystals to become embedded in the lungs after having been inhaled (see Feature 3.2).

Some varieties of asbestos (see Feature 3.2) are examples of minerals with deleterious properties. Other minerals, such as arsenic-containing pyrites, are poisonous when ingested, and still others release toxic fumes when heated. Mineral dust diseases are found in many miners, who may face large occupational exposures. An example is silicosis, a disease of the lungs caused by inhaling quartz dust.

Table 3.4 summarizes the mineral physical properties that we discussed in this section.

Table 3.4 Physical Properties of Minerals

Property	Relation to Composition and Crystal Structure
Hardness	Strong chemical bonds give high hardness. Covalently bonded minerals are generally harder than ionically bonded minerals.
Cleavage	Cleavage is poor if bonds in crystal structure are strong, good if bonds are weak. Covalent bonds generally give poor or no cleavage; ionic bonds are weak and so give excellent cleavage.
Fracture	Type is related to distribution of bond strengths across irregular surfaces other than cleavage planes.
Luster	Tends to be glassy for ionically bonded crystals, more variable for covalently bonded crystals.
Color	Determined by kinds of atoms or ions and trace impurities. Many ionically bonded crystals are colorless. Iron tends to color strongly.
Streak	Color of fine powder is more characteristic than that of massive mineral because of uniformly small size of grains.
Density	Depends on atomic weight of atoms or ions and their closeness of packing in crystal structure. Iron minerals and metals have high density; covalently bonded minerals have more open packing and so have lower density.
Crystal habit	Depends on planes of atoms or ions in a mineral's crystal structure and the typical speed and direction of crystal growth.



EARTH ISSUES

3.2 Asbestos: Health Hazard, Overreaction, or Both?

In the past two decades, mention of asbestos—once used extensively as a fireproof insulator and flame retardant in plaster, ceiling and floor tile, and automobile insulation—has come to provoke fear. Asbestos has been linked to several fatal lung diseases—such as asbestosis (characterized by progressive lung stiffening and difficulty in breathing) and mesothelioma, a cancer that attacks the lining of the lung. The specific link seems to be heavy exposure to certain minerals lumped under the commercial name *asbestos*. The exact way in which these substances cause the diseases is still not well understood, but the sharp fibrous crystal habit of some of the minerals has been implicated.

The health problems associated with exposure to asbestos came to public attention when lawyers representing workers and their families brought class-action lawsuits against some of the major companies that fabricated asbestos products. The lawsuits accused the companies of responsibility for the deaths and disabilities of large numbers of people formerly employed in asbestos factories. In the wake of settlements awarded as a result of these lawsuits, some of the companies went bankrupt. The public became intensely concerned about asbestos-containing materials in schools, hospitals, and other public and private buildings. Many states now require disclosure of such materials during negotiations for the sale of private homes.

Most responsible scientists think that the frenzied concern about all forms of asbestos is an overreaction. At the center of this debate lies mineralogy.

Six distinct minerals are lumped under the commercial term *asbestos*: chrysotile, a sheet silicate member of the serpentine group; crocidolite, a double-chain silicate member of the amphibole group; and four other double-chain silicates in the serpentine group. Although crocidolite does form sharp fibers and has been heavily implicated in lung diseases, many of the other minerals do not form such fibers and have not been associated with lung disease. U.S. government regulations nevertheless apply to all of these minerals.

Physicians and mineralogists hold widely varying opinions about whether all forms of asbestos should be eliminated from buildings and factories. Any decision must consider several facts. First, heavy exposure to croci-

dolite is dangerous—especially for smokers, who are much more prone to asbestos-related lung diseases than are nonsmokers. Prolonged occupational exposure, such as of workers in asbestos factories, to some other forms of asbestos also may create a danger.

Abundant evidence exists, however, to indicate that people exposed for long periods of time to moderate amounts of chrysotile, the most commonly used asbestos in North America, show no asbestos-related lung disease. The lack of a correlation between exposure to specific asbestos minerals, verified by laboratory analysis, and the occurrence of specific lung diseases also contributes to confusion about the danger of exposure to asbestos. The situation is particularly ambiguous with respect to the danger posed to the general population by asbestos in large public buildings.

Many medical scientists and mineralogists doubt that we need to spend the \$50 billion to \$150 billion that it would cost to clean up relatively harmless chrysotile and the four forms of amphibole that do not form sharp fibers. Before any decision can be made with certainty, we need more mineralogical evaluation and additional medical studies to determine the nature of the problem confronting us.



Asbestos (chrysotile). Fibers are readily combed from the solid mineral. [Runk/Schoenberger/Grant Heilman Photography.]



Minerals and the Biological World

The crystal habit and chemical composition of some minerals have made them important in the biological world. The simplest examples are the calcium carbonate minerals calcite and aragonite, used as shell materials by a wide range of invertebrate animals such as clams and oysters. We have only to feel our own bones to recognize the importance of apatite, a calcium phosphate mineral that makes up vertebrate bone.

SUMMARY

What is a mineral? Minerals, the building blocks of rocks, are naturally occurring, inorganic solids with specific crystal structures and chemical compositions that either are fixed or vary within a defined range. A mineral is constructed of atoms, the small units of matter that combine in chemical reactions. An atom is composed of a nucleus of protons and neutrons, surrounded by electrons. The atomic number of an element is the number of protons in its nucleus, and its atomic mass is the sum of the masses of its protons and neutrons.

How do atoms combine to form the crystal structures of minerals? Chemical substances react with one another to form compounds either by gaining or losing electrons to become ions or by sharing electrons. The ions in a chemical compound are held together by ionic bonds, which form by electrostatic attraction between positive ions (cations) and negative ions (anions). Atoms that share electrons to form a compound are held together by covalent bonds. When a mineral crystallizes, atoms or ions come together in the proper proportions to form a crystal structure, which is an orderly three-dimensional geometric array in which the basic arrangement is repeated in all directions.

What are the major rock-forming minerals? Silicates, the most abundant minerals in Earth's crust, are crystal structures built of silicate tetrahedra linked in various ways. Tetrahedra may be isolated (olivines) or in single chains (pyroxenes), double chains (amphiboles), sheets (micas), or frameworks (feldspars). Carbonate minerals are made of carbonate ions bonded to calcium or magnesium or both. Oxide minerals are compounds of oxygen and metallic elements. Sulfide and sulfate minerals are composed of sulfur atoms in combination with metallic elements.

What are the physical properties of minerals? A mineral's physical properties, which indicate its composition and structure, include hardness—the ease with which its surface is scratched; cleavage—its ability to split or break

along flat surfaces; fracture—the way in which it breaks along irregular surfaces; luster—the nature of its reflection of light; color—imparted by transmitted or reflected light to crystals, irregular masses, or a streak (the color of a fine powder); density—the mass per unit volume; and crystal habit—the shapes of individual crystals or aggregates.

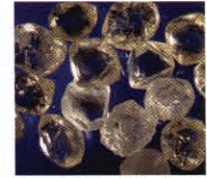
Minerals You Should Know



amphibole



calcite



diamond



dolomite



feldspar



garnet



gypsum



halite



hematite



kaolinite



mica



olivine



pyrite



pyroxene



quartz

[Row 1: George Whiteley/Photo Researchers; Chip Clark; Charles O'Rear/Corbis. Row 2: Charles D. Winters/Photo Researchers; Chip Clark; Andrew Romeo—coolrox.com. Row 3: All by Chip Clark. Row 4: Vincent Cronin; Chip Clark; Chip Clark. Row 5: All by Chip Clark.]

Key Terms and Concepts

anion (p. 54)	hardness (p. 63)
atom (p. 53)	ionic bond (p. 56)
atomic mass (p. 53)	isotope (p. 53)
atomic number (p. 53)	luster (p. 66)
cation (p. 54)	metallic bond (p. 56)
chemical reaction (p. 54)	mineral (p. 52)
cleavage (p. 65)	mineralogy (p. 51)
color (p. 66)	Mohs scale of hardness (p. 63)
covalent bond (p. 56)	neutron (p. 53)
crystal (p. 57)	nucleus (p. 53)
crystal habit (p. 68)	polymorph (p. 58)
crystallization (p. 56)	precipitate (p. 58)
density (p. 67)	proton (p. 53)
electron (p. 53)	specific gravity (p. 67)
electron sharing (p. 54)	streak (p. 66)
electron transfer (p. 54)	
fracture (p. 66)	

Exercises



This icon indicates that there is an animation available on the Web site that may assist you in answering a question.

1. Define a mineral.
2. What is the difference between an atom and an ion?
3. Draw the atomic structure of sodium chloride.
4. What are two types of chemical bonds?
5. What are the two polymorphs of carbon?
6. List the basic structures of silicate minerals.
7. How does the cleavage of mica relate to its atomic structure?
8. Name three groups of minerals, other than silicates, based on their chemical composition.
9. What two factors account for the densities of mantle minerals?
10. How would a field geologist measure hardness?

11. What mineral tests would you conduct to distinguish hematite from magnetite?

12. What is the difference between the carbonate minerals calcite and dolomite?

13. Which of the asbestos minerals poses a health hazard?

Thought Questions



This icon indicates that there is an animation available on the Web site that may assist you in answering a question.

1. Joan and Alex are comparing rubies. Joan's is natural and Alex's is synthetic. Are both of them looking at minerals? Why or why not?

2. Hydrogen (H), the lightest element, has an atomic number of 1 and an atomic mass of 1.008 in nature. What does this information tell you about possible isotopes of hydrogen?

3. Draw a simple diagram to show how silicon and oxygen in silicate minerals share electrons. Model your diagram on Figure 3.5.

4. Use iron and magnesium in silicate minerals to illustrate cation substitution.

5. Diopside, a pyroxene, has the formula $(\text{Ca},\text{Mg})_2\text{Si}_2\text{O}_6$. What does this formula tell you about its crystal structure and cation substitution?

6. Oxygen exists as three isotopes with atomic masses of exactly 16, 17, and 18. The atomic mass of oxygen found in nature is approximately 16. What does this information tell you about the relative abundance of the three isotopes in nature?

7. In some bodies of granite, we can find very large crystals, some as much as a meter across, yet these crystals tend to have few crystal faces. What can you deduce about the conditions under which these large crystals grew?

8. What physical properties of sheet silicates are related to their crystal structure and bond strength?


9. How might you identify and differentiate between a single- and a double-chain silicate?

10. What physical properties would make calcite a poor choice for a gemstone?

11. Choose two minerals from Appendix 5 that you think might make good abrasive or grinding stones for sharpening steel, and describe the physical property that causes you to believe they would be suitable for this purpose.

12. Aragonite, with a density of 2.9 g/cm^3 , has exactly the same chemical composition as calcite, with a density of 2.7 g/cm^3 . Other things being equal, which of these two minerals is more likely to have formed under high pressure?

13. What properties of talc make it suitable for face and body powder?

 14. There are at least eight physical properties one can use to identify an unknown mineral. Which ones are most useful in discriminating between minerals that look similar? Describe a strategy that would allow you to determine that an unknown clear calcite crystal is indeed not the same as a known clear crystal of quartz.

15. There is much controversy over the removal of asbestos from buildings in the United States and Canada. It is clear that some forms of asbestos do pose a health hazard. Based on what you have learned about mineral structures, what aspect of the structure of asbestos causes the hazard? Given the double-chain silicate structure of asbestos, are other double-chain silicates potentially dangerous?

16. Coal, which forms from decaying vegetation and is, therefore, a natural substance, is not considered to be a mineral. However, when coal is heated to high temperatures and buried in high-pressure areas, it transforms into the mineral graphite. Why is it, then, that coal is not considered a mineral but graphite is? Explain your reasoning.

17. Back in the late 1800s, gold miners used to “pan” for gold by placing sediment from rivers into a pan and filtering water through the pan while swirling the pan’s content. Specifically, the miners wanted to be certain that they had found real gold and not pyrite (“fool’s gold”). Why did this method work? What mineral property does the process of panning for gold utilize? What is another possible method for distinguishing between gold and pyrite?

Short-Term Project

Why Is the Hope Diamond Blue?

In late 1955, Robert H. Wentorf, Jr., achieved something close to alchemy. He bought a jar of peanut butter at a local food co-op, took it to his lab, and then turned a glob of the spread into a few tiny (green) diamonds.* After all, peanuts are rich in proteins, which are rich in nitrogen. Synthetic diamonds are often black due to inclusions of graphite, and traces of nitrogen within the crystal structure can turn diamonds brown, yellow, or green.

*Ivan Amato, Diamond fever. *Science News*, August 4, 1990, p. 72.

Diamonds form in the upper mantle at depths below about 200 km where temperatures and pressures cause graphite, diamond’s sister mineral, to collapse into a more tightly packaged crystal structure (see Figure Story 3.11). Most diamonds weigh less than 1 carat (0.2 gram) and are colorless, pale yellow, or brown. Larger diamonds, especially colored ones, are rare. The largest faceted diamond is the yellow 545.67-carat Golden Jubilee, unveiled in 1995. The Hope Diamond, on display at the Smithsonian Institute, may be the best-known gemstone in the world. It is a very rare 45-carat blue diamond.

What produces the color of gems and minerals? Color is produced by the interaction of light with matter. You know how a prism or even water drops break white light into a spectrum or rainbow of colored light. When light hits the surface of or penetrates a crystal, it interacts with atoms; some components of the light may be absorbed while others are transmitted. As white light passes through the Hope diamond, the crystal absorbs red light and transmits blue.

Why are many diamonds colorless and others blue, red, yellow, green, or brown? Trace amounts of impurities and imperfections in the crystal structure of a mineral can change how the mineral interacts with light and cause it to be colored. Although diamonds are pure carbon, it takes only one atom of another element among the million atoms to turn a diamond blue. Rubies and sapphires are both crystals of aluminum oxide; yet rubies are red and sapphires are blue. Go to <http://www.whfreeman.com/understandingearth> to figure out what causes the Hope diamond to be blue, rubies to be red, and sapphires to be blue.

Short-Term Team Projects

Asbestos

Children were in danger. News reports of asbestos in the New York City schools touched off a wave of public outrage, and the Board of Education postponed the start of the 1993 school year for three weeks to complete an asbestos-removal program.

Reports of asbestos in public buildings almost always focus on the risk of lung disease. Seldom, however, do these reports include interviews with mineralogists. As a result, the public knows too little about asbestos to ask the right questions and make an informed judgment.

You now have the chance to educate the public. Working in a team of four students over the next two weeks, prepare a half-hour radio program representing a variety of perspectives on the asbestos issue. The program will show how useful a basic knowledge of mineralogy can be in deciding important policy questions. Assemble a cast of experts with opposing positions on the issue. From what

disciplines would they come? With what arguments and facts would they support their positions? Write a script for the program and deliver an oral summary of your list of experts and their positions.

Suggested Readings

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