

MINERALS: THE BUILDING BLOCKS OF ROCKS

MINERALS

CHAPTER OUTLINE

Minerals

The Composition of Minerals

The Structure of Minerals

Physical Properties of Minerals

Mineral Classes

Orange-red crystals of garnet (variety grossular) and smaller crystals of yellowish green pyroxene (variety diopside) from the Jeffrey Mine, Asbestos, Quebec. (Photo courtesy of Thomas Spann/Mineral Masterpiece)

Earth's crust and oceans are the source of a wide variety of useful and essential minerals (Figure 2.1). In fact, practically every manufactured product contains materials obtained from minerals. Most people are familiar with the common uses of many basic metals, including aluminum in beverage cans, copper in electrical wiring, and gold and silver in jewellery. But some people are not aware that pencil lead contains the greasy-feeling mineral graphite and that baby powder comes from the mineral talc. Moreover, many do not know that drill bits covered with diamonds are employed by dentists to drill through tooth enamel, or that the common mineral quartz is the source of silicon for computer chips. As the mineral requirements of modern society grow, the need to locate additional supplies of useful minerals also grows and becomes more challenging.

All processes studied by geologists are in some way dependent on the properties of minerals. Volcanic eruptions, plate tectonics and mountain building, weathering and erosion, and even earthquakes involve rocks and minerals. A basic knowledge of Earth materials is therefore essential to understanding all geologic phenomena.

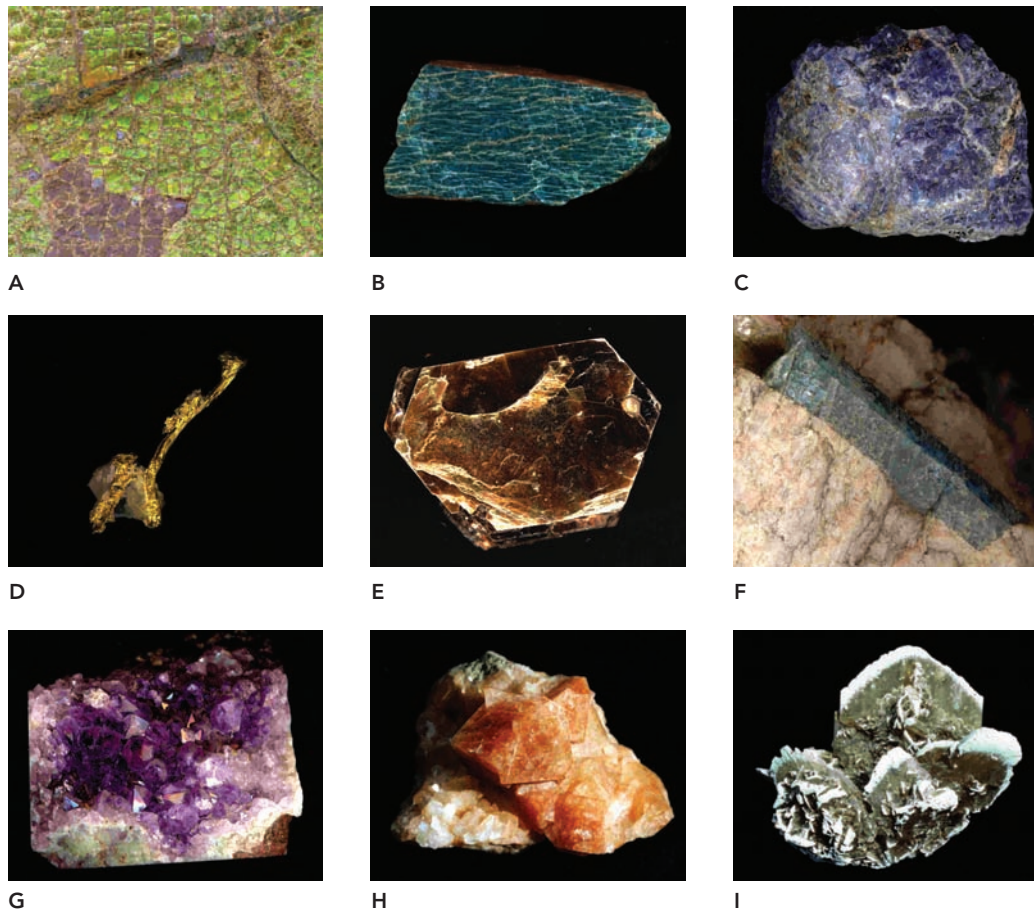
MINERALS



Minerals: Building Blocks of Rocks

Introduction

We start with **mineralogy** because minerals are the building blocks of rocks. Geologists define **minerals** as any naturally occurring inorganic solids that possess an orderly internal structure and a definite chemical composition. Thus, for any Earth material to be



◆ **Figure 2.1** Canadian mineral samples. **A.** Aragonite (as Ammolite; fossil mother of pearl) from Lethbridge, Alberta. **B.** Microcline (variety: amazonite) from Lac Sairs, Quebec. **C.** Sodalite from Bancroft, Ontario. **D.** Gold (on quartz) from Louvricourt Mines, Quebec. **E.** Phlogopite from Baffin Island, Nunavut. **F.** Beryl (variety: emerald) from Quadeville, Ontario. **G.** Quartz (variety: amethyst) from Loon, Ontario. **H.** Chabazite from Wasson's Bluff, Nova Scotia. **I.** Gypsum (variety: selenite) from Swift Current Creek, Saskatchewan. (Photos **A–G** by C. Tsujita; photos **H** and **I** by Arnim Walter; specimens **B–I** courtesy of the Department of Earth Sciences, the University of Western Ontario)

considered a mineral it must exhibit the following characteristics:

1. It must occur naturally.
2. It must be a solid.
3. It must possess an orderly internal structure; that is, its atoms must be arranged in a definite pattern.
4. It must have a definite chemical composition that can vary within specified limits.
5. It is *usually* inorganic (although mineral formation can, in some cases, be mediated by biological processes).

When geologists use the term *mineral*, only those substances that meet these five criteria are considered minerals. Consequently, synthetic diamonds and other useful materials produced by chemists are not considered minerals. Rocks, however, are more loosely defined. Simply, a **rock** is any solid mass of mineral or mineral-like matter that occurs naturally as part of our planet. A few rocks are composed of one mineral. Limestone, for example, is composed of impure masses of the mineral calcite. However, most rocks, like granite (shown in Figure 2.2), occur as aggregates of different minerals, each of which retains its characteristic physical and chemical properties. Here, the term

aggregate implies that the minerals are joined in such a way that the properties of each mineral are retained. Note that you can easily distinguish the mineral constituents of the sample of granite shown in Figure 2.2.

Some rocks are composed of nonmineral matter. These include the volcanic rocks *obsidian* and *pumice*, composed of noncrystalline, glassy substances; and *coal*, which consists of organic matter.

Because the properties of rocks are determined largely by the chemical composition and internal structure of the minerals they contain, we will first study minerals in this chapter, and then the major rock types in subsequent chapters.

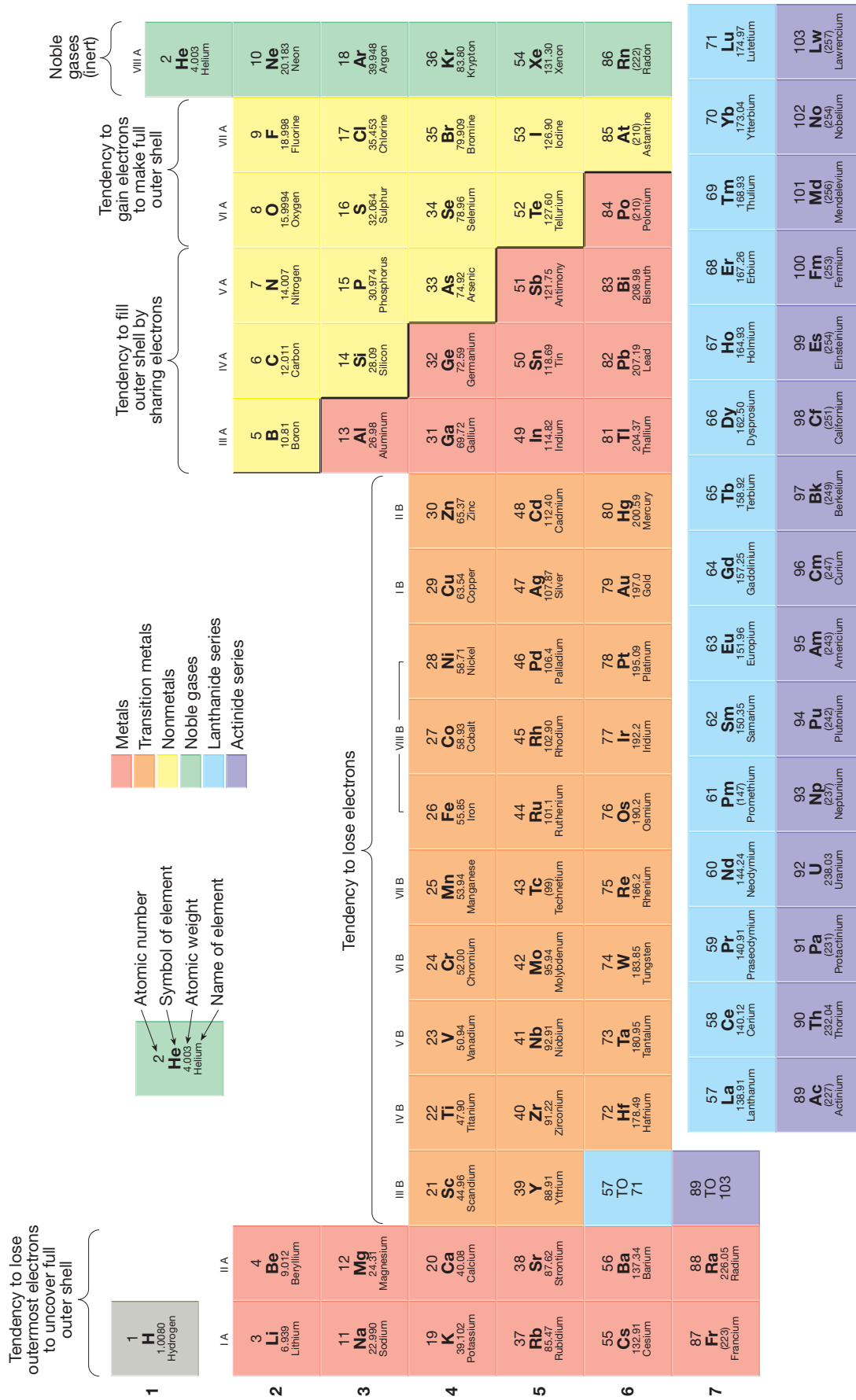
THE COMPOSITION OF MINERALS

Elements

Each of Earth's approximately 4000 minerals is uniquely defined by its chemical composition and internal structure. In other words, every sample of the same mineral contains the same *elements* joined together in a consistent, repeating pattern. At present, 113 elements are known. Of these, 90 are naturally occurring (Figure 2.3). Some minerals, such as



◆ **Figure 2.2** Most rocks are aggregates of several kinds of minerals.

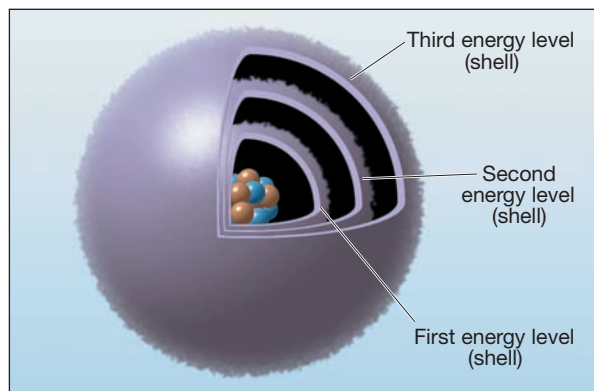


◆ Figure 2.3 Periodic table of the elements.

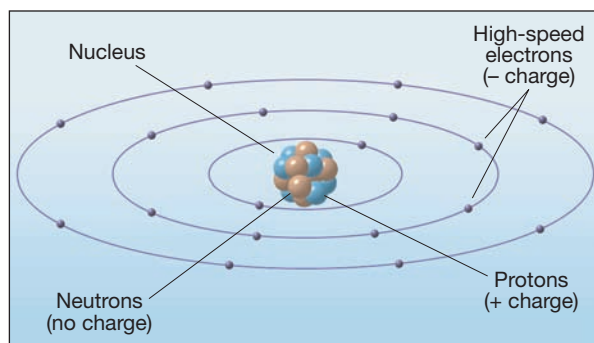
gold and sulphur, consist entirely of one element. But most minerals are a combination of two or more elements joined to form a chemically stable and electrically neutral compound. To understand better how elements combine to form molecules and compounds, we must first consider the **atom** (*a* = not, *tomos* = cut), the smallest part of matter that cannot be chemically split. It is this extremely small particle that does the combining.

Atomic Structure

The central part of an atom, the nucleus, consists of a bundle of particles called **protons** and **neutrons**. Each proton has a positive electrical charge while each neutron has no charge. Both types of particles are about equal in size and density. Together they constitute nearly all of an atom's mass. Rapidly orbiting the nucleus are tinier, lighter, negatively charged particles called **electrons** that form concentric, spherically shaped energy level **shells** (Figure 2.4A).



A



B

◆ **Figure 2.4** Two models of the atom. (Note that these models are not drawn to scale.) **A.** Model of an atom showing spherically shaped, concentric electron energy level shells surrounding a central nucleus of protons and neutrons. Electrons are minuscule in size compared with protons and neutrons, and the relative space between the nucleus and electron shells is much greater than illustrated. **B.** A more simplified view of the atom, depicting high-speed electrons orbiting the nucleus in a single plane.

In any given atom, the number of electrons equals the number of protons, resulting in an electrically neutral state for the atom as a whole. To make it easier to visualize the electrons in their shells, it is convenient to depict electrons orbiting the nucleus in a single plane (Figure 2.4B).

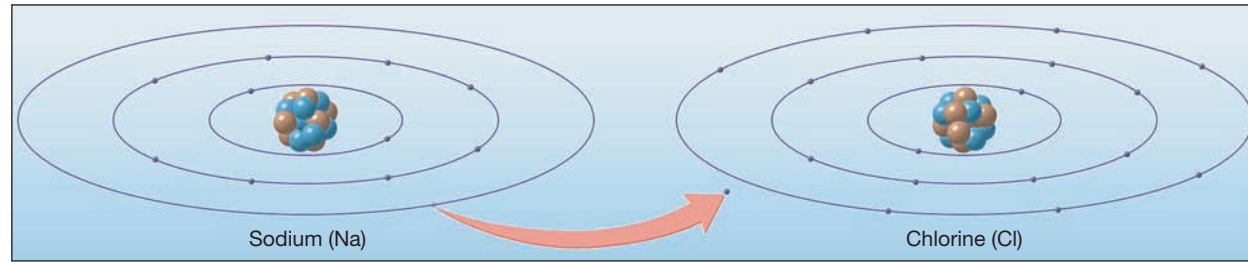
An atom of a specific element is characterized by a certain number of protons. For example, all carbon atoms have six protons, all oxygen atoms have eight protons, and so forth. This unique number is called the **atomic number**. This differs from the **atomic weight**, which corresponds approximately to the total number of protons and neutrons in its nucleus (each accounting for one unit of mass), plus a comparatively minuscule mass contribution from electrons. It should be noted that while the number of protons (and matching number of electrons) is explicitly represented in the periodic table of elements (Figure 2.3) by the atomic number, the number of neutrons is only implied as part of the atomic weight. Determining the approximate number of neutrons merely requires the subtraction of the atomic number from the atomic weight.

For most elements, the stability of their atoms is dictated by the number of electrons present in their energy level shells. The innermost shell of an atom can hold a maximum of two electrons. Shells surrounding this innermost shell can hold a maximum of eight electrons. For atoms of elements with more than two electrons, the most stable electron configuration occurs when the number of electrons in the outermost shell equal eight. This requirement for stability is satisfied in atoms of the so-called “noble gases” (e.g., argon), which are the least chemically active elements. Other elements—those with fewer than eight electrons in their outermost shell—tend to combine with other atoms in order to achieve this stable configuration. Such combination is achieved through the interaction of the outermost electrons, called **valence electrons**.

Bonding

Elements combine with each other to form a wide variety of more complex substances. The strong attractive force linking atoms together is called a **chemical bond**. When chemical bonding joins two or more elements together in definite proportions, the substance is called a **compound**. Minerals are chemical compounds. In this book only the two main types of bonding are summarized.

IONIC BONDS Perhaps the easiest type of bond to visualize is an **ionic bond**. In ionic bonding, one

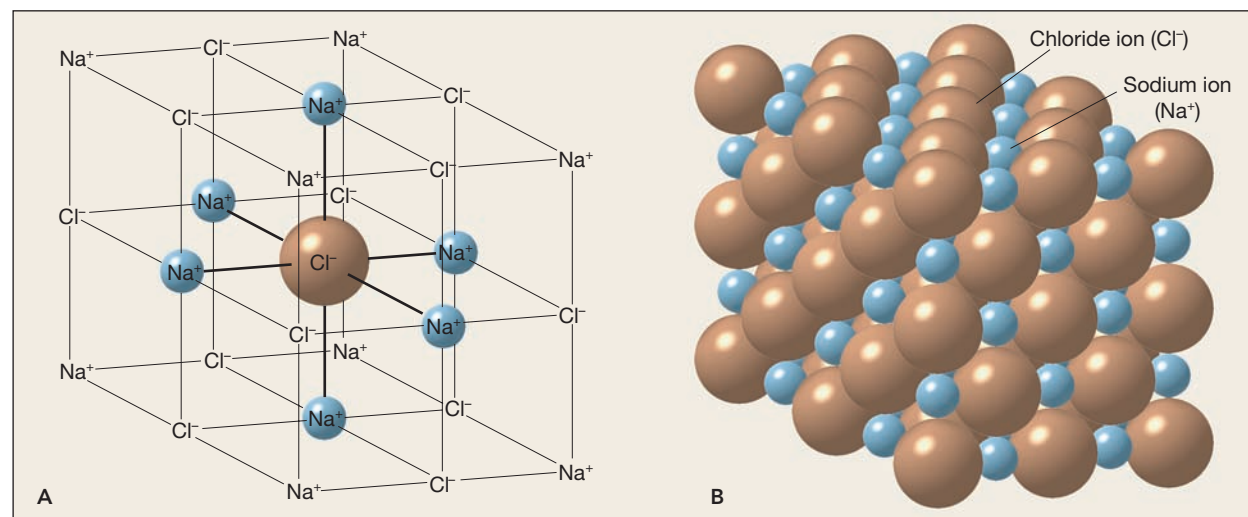


◆ **Figure 2.5** Chemical bonding of sodium and chlorine through the transfer of the lone outer electron from a sodium atom to a chlorine atom. The result is a positive sodium ion (Na^+) and a negative chloride ion (Cl^-). Bonding to produce sodium chloride (NaCl) is due to electrostatic attraction between the positive and negative ions.

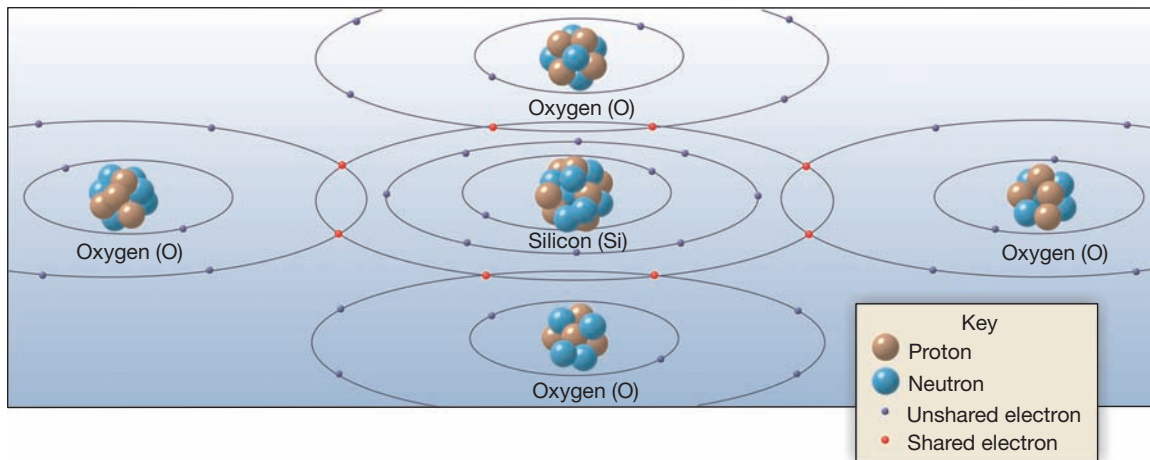
or more electrons are transferred from one atom to another. Simply, one atom gives up some electrons and the other receives them. A common example of ionic bonding is the joining of sodium (Na) and chlorine (Cl) to produce sodium chloride (NaCl or common table salt). This bond is shown in Figure 2.5. Notice that sodium gives up a single electron to chlorine to form an electrically neutral compound. Once electron transfer occurs, the atoms themselves are no longer electrically neutral. By giving up one electron, a neutral sodium atom becomes *positively charged*. Similarly, by acquiring one electron, the neutral chlorine atom becomes *negatively charged*. Such atoms, which have an electrical charge because they have a deficit or surplus of electrons, are called **ions**. An atom that picks up an extra electron and becomes negatively charged is called an *anion*. An atom that loses an electron and becomes positively charged is called a *cation*. Electron sharing produces a covalent bond.

We know that ions with like charges repel and those with unlike charges attract. Thus, an *ionic bond* is the attraction of oppositely charged ions to one another, producing an electrically neutral compound. Figure 2.6 illustrates the arrangement of sodium and chloride ions in ordinary table salt. Notice that salt consists of alternating sodium and chloride ions, positioned in such a manner that each positive ion is attracted to and surrounded on all sides by negative ions, and vice versa. This arrangement maximizes the attraction between ions with unlike charges, while minimizing the repulsion between ions with like charges. Thus, *ionic compounds consist of an orderly arrangement of oppositely charged ions assembled in a definite ratio that provides overall electrical neutrality*.

The properties of a chemical compound are *dramatically different* from the properties of the elements composing it. For example, chlorine is a green, poisonous gas that is so toxic it was used during World



◆ **Figure 2.6** Schematic diagrams illustrating the arrangement of sodium and chloride ions in table salt. **A.** Structure has been opened up to show arrangement of ions. **B.** Actual ions are closely packed.



◆ **Figure 2.7** Silica, the basic building block of all silicate minerals, consists internally of a central silicon atom that shares a pair of electrons with each of four neighbouring oxygen atoms, forming strong covalent bonds. This diagram, depicting all atoms in a single plane, is a two-dimensional representation of what is actually a three-dimensional structure—the silica tetrahedron (depicted later in Figure 2.21).

War I as a chemical weapon. Sodium is a soft, silvery metal that reacts vigorously with water and, if held in your hand, can burn severely. Together, however, these atoms produce the compound sodium chloride (table salt), a clear crystalline solid that is essential for human life. This example illustrates an important difference between a rock and a mineral. Most *minerals* are *chemical compounds* with unique properties that are very different from the elements that compose them. Most *rocks*, however, are *mixtures* of minerals, with each mineral retaining its own identity.

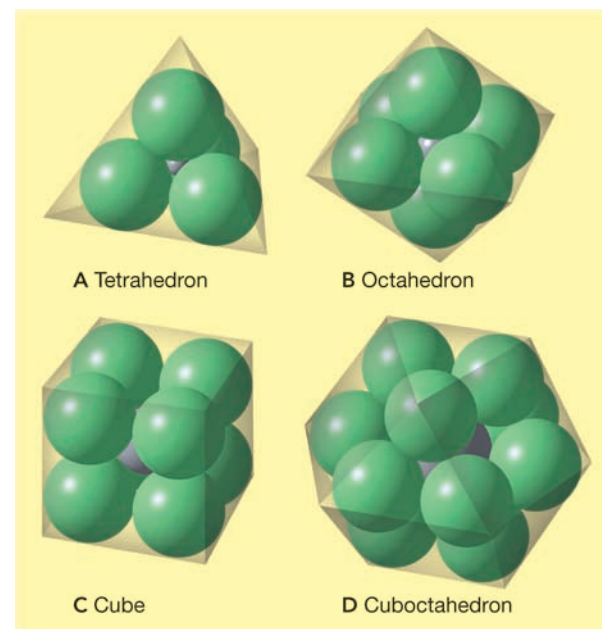
COVALENT BONDS Not all atoms combine by transferring electrons to form ions. Other atoms *share* electrons.

The most common mineral group, the silicates, contains the element silicon, which readily forms covalent bonds with oxygen. Figure 2.7 illustrates the sharing of a pair of electrons between one silicon and two oxygen atoms to form a molecule of silica (SiO_2). Thus, each atom has acquired, through cooperative action, an electron balance for an electrically neutral compound.

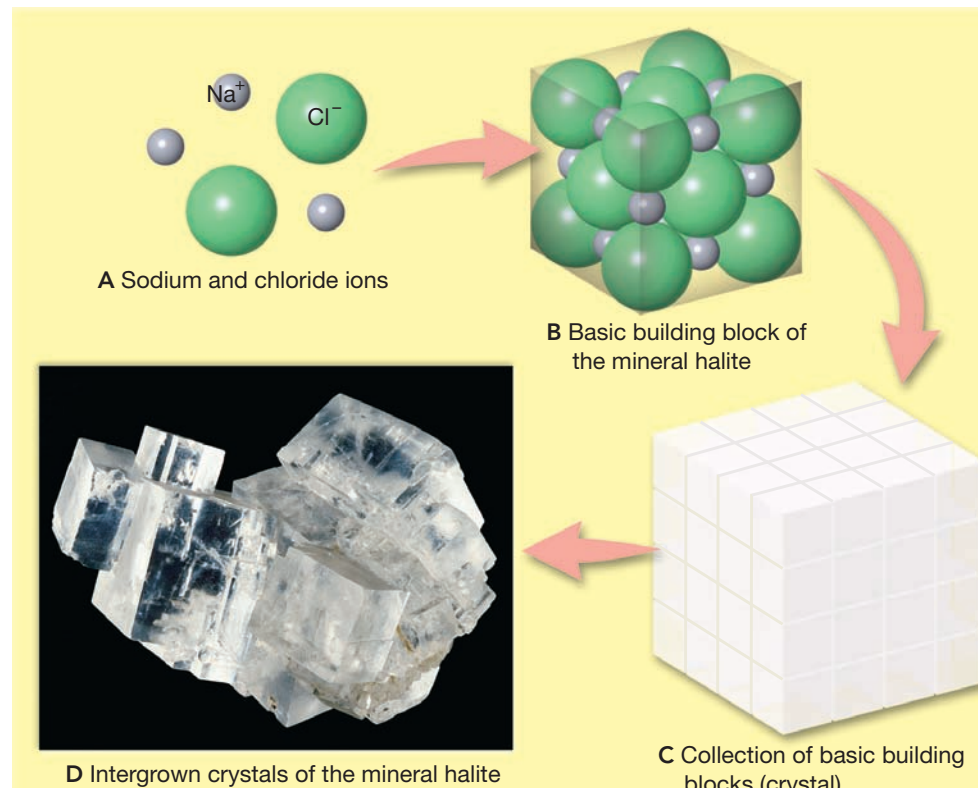
THE STRUCTURE OF MINERALS

A mineral is composed of an ordered array of atoms chemically bonded to form a particular crystalline structure. This orderly packing of atoms is reflected in the regularly shaped objects we call crystals (see chapter-opening photo).

For those compounds formed by ions, the internal atomic arrangement is determined partly by the charges on the ions, but even more so by the size of the ions involved. To form stable ionic compounds, each positively charged ion is surrounded by the largest number of negative ions that will fit, while maintaining overall electrical neutrality, and vice versa. Figure 2.8 shows ideal packing arrangements for ions of various sizes.



◆ **Figure 2.8** Ideal geometric packing for positive (purple) and negative (green) ions of various size ratios.



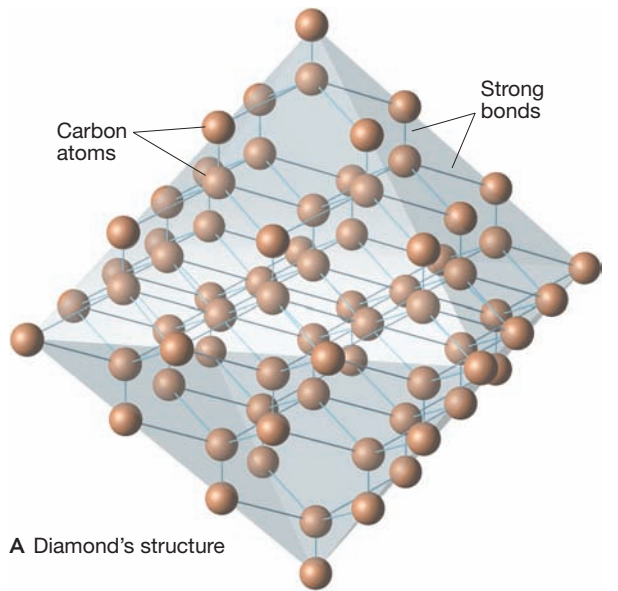
◆ **Figure 2.9** The structure of sodium chloride. **A, B.** The orderly arrangement of sodium and chloride ions in the mineral halite. **C, D.** The orderly arrangement at the atomic level produces the regularly shaped salt crystals shown in this photograph. (Photo by M. Claye/Jacana Scientific Control/Photo Researchers, Inc.)

Let's examine the geometric arrangement of sodium and chloride ions in the mineral halite (common salt; Figure 2.9). We see in Figure 2.9A that the sodium and chloride ions pack together to form a cube-shaped internal structure (Figure 2.9B). Also note that the orderly arrangement of ions found at the atomic level (Figure 2.9C) is reflected on a much larger scale in the cube-shaped halite crystals shown in Figure 2.9D. Like halite, all samples of a particular mineral contain the same elements, joined together in the same orderly arrangement.

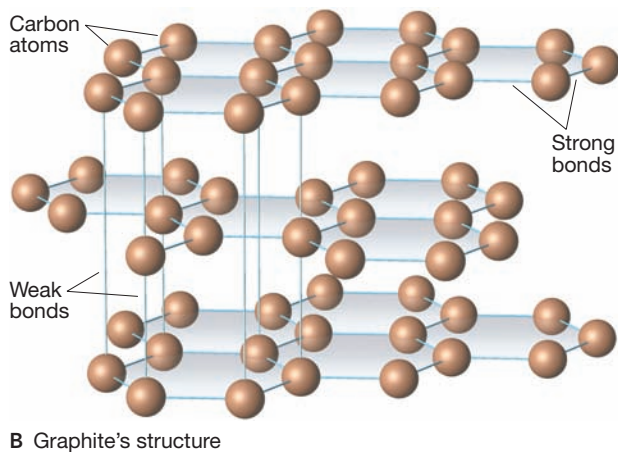
Some elements are able to join together in more than one type of geometric arrangement. This means that two or more minerals can share the same chemical composition and yet exhibit very different physical characteristics. Minerals of this type are said to be **polymorphs** (*poly* = many, *morph* = form). Graphite and diamond are good examples of polymorphism because they both consist exclusively of carbon yet have drastically different properties (Figure 2.10). Graphite is the soft, grey material

of which pencil lead is made, whereas diamond is the hardest known mineral. They are different because of how they are formed. Diamonds form at depths approaching 200 kilometres, where the compact structure shown in Figure 2.10A is produced by extreme pressures. Graphite, conversely, forms under low pressure and temperature and consists of sheets of carbon atoms that are widely spaced and weakly held together (Figure 2.10B). Because these carbon sheets will easily slide past one another, graphite makes an excellent lubricant.

Scientists have learned that by heating graphite under high pressure, they can produce diamonds. Although synthetic diamonds are generally not gem quality, they have many industrial uses. In nature, some minerals transform from one polymorph into another when changes in temperature and pressure occur in their surrounding environment. For example, when rocks containing *olivine* are carried to greater depths by a subducting plate, the olivine will convert to a more compact form called *spinel*.



Diamond



Graphite

◆ **Figure 2.10** Comparing the structures of diamond and graphite. Both are natural substances with the same chemical composition: carbon atoms. Nevertheless, their internal structure and physical properties reflect the fact that each forms in a very different environment. **A.** All carbon atoms in diamond are covalently bonded into a compact, three-dimensional framework, which accounts for the extreme hardness of the mineral. **B.** In graphite the carbon atoms are bonded into sheets that are joined in a layered fashion by very weak electrical forces. These weak bonds allow the sheets of carbon to readily slide past each other, making graphite soft and slippery, and thus useful as a dry lubricant. (Photo **A** by photographer Dane Pendland, courtesy of Smithsonian Institute; photo **B** by E. J. Tarbuck)

PHYSICAL PROPERTIES OF MINERALS



Matter and Minerals Physical Properties of Minerals

Minerals are solids formed primarily by inorganic processes. Each mineral has an orderly arrangement of atoms (crystalline structure) and a definite chemical composition, which give it a unique set of physical properties. Some properties, such as those described below, can be directly observed and/or

tested by simple means and therefore are especially useful in mineral identification.

Crystal Habit (Shape)

Crystal habit is the external expression of a mineral that reflects the orderly internal arrangement of atoms. Figure 2.11A illustrates the characteristic habit of the iron-bearing mineral pyrite.

Generally, when a mineral can form without space restrictions, it will develop individual crystals with well-formed crystal faces. Some minerals, like quartz,



A



B

◆ **Figure 2.11** Crystal form is the external expression of a mineral's orderly internal structure. **A.** Pyrite, commonly known as "fool's gold," often forms cubic crystals. They may exhibit parallel lines (striations) on the faces. **B.** Quartz sample that exhibits well-developed hexagonal crystals with pyramid-shaped ends. (Photo **A** courtesy of E. J. Tarbuck; photo **B** by Breck P. Kent)

have a distinctive crystal habit (Figure 2.11B). However, the growth of individual crystals is often interrupted by competition for space, resulting in an intergrown mass of crystals lacking obvious crystal habit. This is one of the reasons why you must be able to recognize other diagnostic mineral properties, such as those described below, to identify minerals accurately.

Lustre

Lustre is the appearance or quality of light reflected from the surface of a mineral crystal. Some minerals like pyrite (Figure 2.11A), look like polished metal and have a *metallic lustre*. Others, like quartz (Figure 2.11B), have a *nonmetallic lustre* and can be further described as vitreous (glassy, as in the case of quartz), pearly, silky, resinous, or earthy (dull). Still other minerals appear somewhat metallic in lustre and are said to be submetallic.

Colour

Although **colour** of a mineral specimen is often obvious, it is not always diagnostic. For example, pure quartz is clear and colourless (see Figure 2.11B), but the addition of slight impurities (e.g., iron, chromium) can impart hues of colours of purple (amethyst, as shown in Figure 2.1), pink (rose quartz), yellowish orange (citrine), or even dark brown to black (smoky quartz) (Figure 2.12).

Streak

Streak is the colour of a mineral in its powdered form and is obtained by rubbing the mineral across a piece of unglazed porcelain known as a *streak plate* (Figure 2.13). Although the colour of a mineral can vary from sample to sample, the streak (e.g., reddish brown in hematite) usually does not and is therefore a more reliable property.



◆ **Figure 2.12** Because of the presence of slight impurities, minerals, such as quartz, can occur in a wide range of colours. (Photo courtesy of E. J. Tarbuck)



◆ **Figure 2.13** Although the colour of a mineral may not be helpful in identification, the streak, which is the colour of the powdered mineral, can be very useful. (Photo by Dennis Tasa)

Hardness

One of the most useful properties is **hardness**, a measure of a mineral's resistance to abrasion or scratching. By rubbing a mineral of unknown hardness against one of known hardness, or vice versa, a numeric value can be obtained by using the **Mohs scale** of hardness. This scale consists of 10 minerals arranged in order from 1 (softest) to 10 (hardest), as shown in Table 2.1.

Any mineral of unknown hardness can be compared with the scale minerals or with other objects of known hardness. A fingernail has a hardness of 2.5; a copper penny, 3.5; and a piece of glass, 5.5. Gypsum is 2, and can be scratched

TABLE 2.1 Mohs Scale of Hardness

Relative Scale	Mineral	Hardness of Some Common Objects
10 (Hardest)	Diamond	
9	Corundum	
8	Topaz	
7	Quartz	6.5 streak plate
6	Potassium feldspar	5.5 glass
5	Apatite	5 knife blade
4	Fluorite	4.5 wire nail
3	Calcite	3 copper penny
2	Gypsum	2.5 fingernail
1 (Softest)	Talc	

with your fingernail; calcite is 3 and will scratch your fingernail but will not scratch glass. Quartz will scratch glass and diamond can scratch itself or any other mineral.

Cleavage

Cleavage (*kleiben* = carve) is the tendency of a mineral to break along planes of weak bonding. Minerals that have cleavage can be identified by the distinctive smooth surfaces produced when the minerals are broken.

The simplest type of cleavage occurs in micas (Figure 2.14). Because they have weak bonds in one planar direction, they cleave to form thin, flat sheets. Some minerals reveal several cleavage planes when broken; others show poor cleavage and still others, such as quartz, have no cleavage at all. When minerals break evenly in multiple directions, cleavage is described as the *number of planes* exhibited and the *angles at which they meet*, as depicted in Figure 2.15).

Do not confuse cleavage with crystal habit (shape). When a mineral exhibits cleavage, it will break into pieces that all have *the same geometry*. By contrast the quartz crystals shown in Figure 2.11B do not have cleavage. If broken, they fracture into shapes that do not resemble each other or the original crystals.



◆ **Figure 2.14** The thin sheets shown here were produced by splitting a mica (muscovite) crystal parallel to its perfect cleavage. (Photo by Chip Clark)

Number of Cleavage Directions	Sketch	Illustration of Cleavage Directions	Example
1			Muscovite
2 at 90°			Orthoclase
2 not at 90°			Amphibole
3 at 90°			Halite
3 not at 90°			Calcite
4			Fluorite

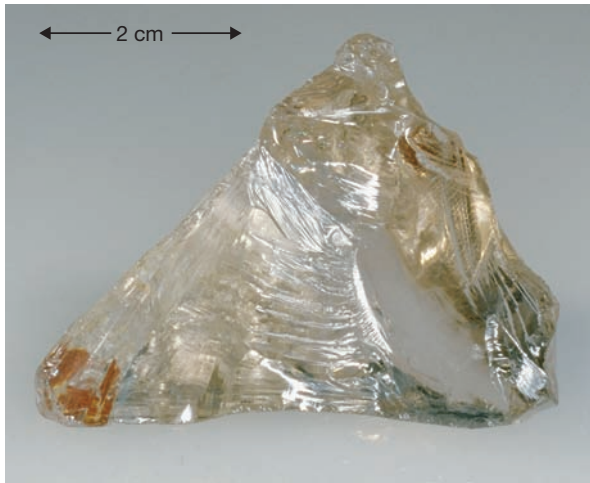
◆ **Figure 2.15** Common cleavage directions exhibited by minerals. (Photos courtesy of E. J. Tarbuck)

Fracture

Minerals having chemical bonds of similar strength in all directions, and therefore lacking the ability to cleave along certain planes within their crystals, may still break or **fracture** in a distinctive manner. Quartz, for example, breaks to form smooth curved surfaces resembling broken glass or the interior of a seashell. This is called *conchoidal fracture* (Figure 2.16). Some minerals break into splinters or fibres. Most minerals, however, fracture irregularly, producing uneven fracture.

Specific Gravity

Specific gravity is a number representing the ratio of the weight of a mineral to the weight of an equal volume of water. For example, if a mineral weighs three times as much as an equal volume of water, its specific gravity is 3. If a mineral feels as heavy as common rocks you have handled, its specific gravity will probably be somewhere between 2.5 and 3. Some metallic minerals have a specific gravity two or three times that of common rock-forming minerals. Galena, which is



◆ **Figure 2.16** Conchoidal fracture. The smooth curved surfaces result when minerals break in a glasslike manner. (Photo by E. J. Tarbuck)



◆ **Figure 2.18** A transparent specimen of calcite showing the property of double refraction. (Photo by S. R. Hicock)

mined for lead (Figure 2.17), has a specific gravity of roughly 7.5, whereas the specific gravity of 24-karat gold is approximately 20.

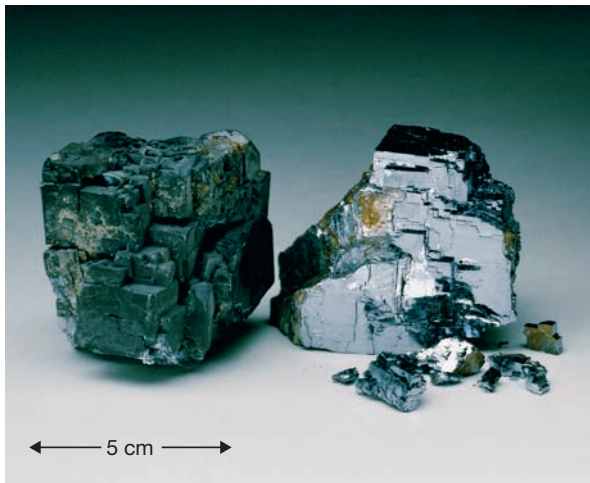
Other Properties of Minerals

In addition to the properties already discussed, there are others that are diagnostic to certain minerals. For example, halite is ordinary salt so it is quickly identified with your tongue. Thin sheets of mica will bend and elastically snap back. Gold is malleable and can be easily shaped. Talc feels soapy and graphite feels greasy. Magnetite has a high iron content and

is attracted to a magnet. Also, many sulphur-bearing minerals smell like rotten eggs when rubbed or scratched.

Some minerals exhibit special optical properties. For example, when a transparent piece of calcite is placed over printed material, the letters appear twice (Figure 2.18). This optical property is known as *double refraction*.

Another diagnostic property of calcite is that it reacts vigorously when brought into contact with acid; any rock containing calcite will immediately effervesce (fizz) when a drop of dilute hydrochloric acid is applied to it (Figure 2.19).



◆ **Figure 2.17** Galena is lead sulphide and, like other metallic ores, has a relatively high specific gravity. (Photo by E. J. Tarbuck)



◆ **Figure 2.19** Calcite vigorously effervesces when brought into direct contact with acid. (Photo by C. Tsujita)

BOX 2.1 GEOLOGY AND POPULAR MEDIA

Kryptonite Discovered! . . . Sort Of



Kryptonite, the fictional substance eagerly sought by villains determined to take over the world, has figured so prominently in comic books, radio, television programs, and movies that it is difficult to imagine a Superman adventure without it. The nature of kryptonite has changed frequently over the history of the Superman franchise, and has been a specific element (not to be confused with the real element of the same name), a metal alloy, a type of rock (as meteorites), and a mineral. Likewise, the colour of kryptonite has varied, although green appears to be the most widely cited. In some stories, kryptonite is simply rock fragments derived from Superman's exploded home planet Krypton; in others it was created from the nuclear explosion that caused Krypton's destruction. Despite such inconsistencies, it is well-established that Superman's powers are significantly weakened if he comes into close contact with kryptonite. In the 2006 movie *Superman Returns*, the composition of kryptonite is revealed

when the camera zooms into the empty glass case (in the Metropolis Museum) from which Lex Luthor has stolen this precious material. Written on the specimen name plate is *sodium lithium boron silicate hydroxide with fluorine*.

Enter the Rio Tinto Group, a mineral exploration company working in the Jadar Valley of Serbia. Discovered in drill cores obtained in 2006 were compact masses of a mineral that had not been previously described. A sample was sent to mineralogist Chris Stanley of the Natural History Museum (London, UK), who, with help from the National Research Council of Canada, established that it was a new mineral species, composed of *sodium lithium boron silicate hydroxide*. By sheer coincidence, the new mineral (later named jadarite) turned out to have a nearly identical chemical composition to the latest flavour of kryptonite featured in *Superman Returns* (minus fluorine). But despite the chemical similarity to kryptonite, this new mineral is neither green nor



◆ **Figure 2.A** Core sample of jadarite, a newly discovered mineral with nearly the same chemical composition as the fictional kryptonite—Superman's least favourite substance.
(© Natural History Museum, London)

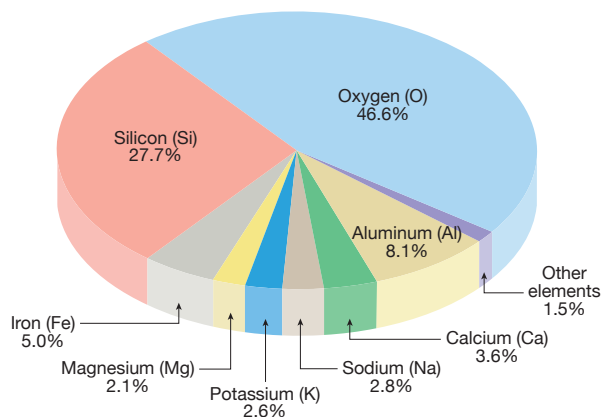
radioactive. It doesn't glow on its own either (although it does fluoresce a pretty pinkish-orange colour under ultraviolet light). So, Superman is safe . . . for now.

MINERAL CLASSES

Minerals: Building Blocks of Rocks Mineral Classes

Approximately 4000 minerals have been named and new ones are identified each year, but only a few dozen are common. Collectively, these few make up most rocks of Earth's crust and, as such, are classified as *rock-forming minerals*. *Eight elements* make up the bulk of these minerals, and represent more than 98 percent (by weight) of continental crust (Figure 2.20). In order of abundance, they are: oxygen (O), silicon (Si), aluminum (Al), iron (Fe), calcium (Ca), sodium (Na), potassium (K), and magnesium (Mg).

Silicon and oxygen combine to form the framework of the most common mineral class, the **silicates**.



◆ **Figure 2.20** Relative abundance of the eight most abundant elements in the continental crust.

The next most common mineral group is the carbonates, of which calcite is the most prominent member.

We will first discuss the silicates and then look at the other mineral classes.

The Silicates

Every silicate mineral contains the elements oxygen and silicon, and most contain one or more additional elements to make the mineral electrically neutral. Other than quartz and its polymorphs, a silicate mineral includes one or more other common elements

that are needed to produce electrical neutrality. Together, these additional elements give rise to hundreds of silicate minerals (Box 2.2).

THE SILICON-OXYGEN TETRAHEDRON All silicates have the same fundamental building block, the **silicon-oxygen tetrahedron** (*tetra* = four, *hedra* = a base). This structure consists of four oxygen ions (each with a 2- charge) surrounding a much

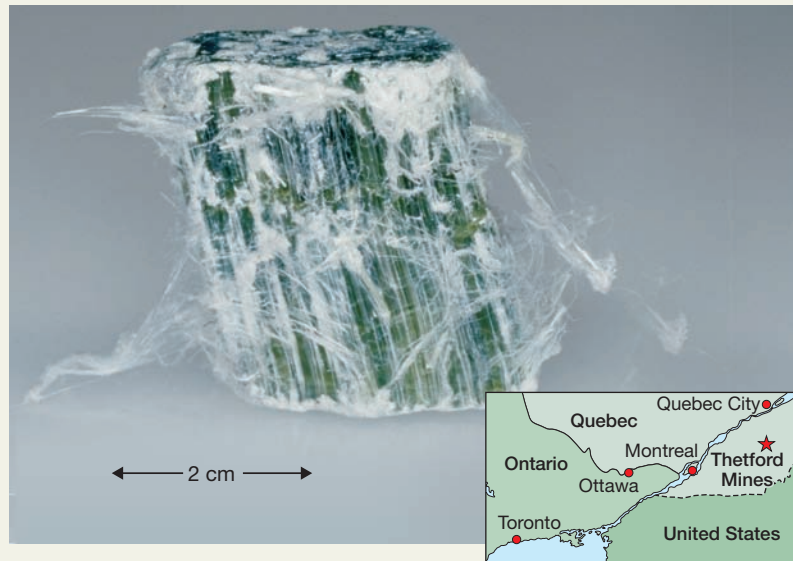
BOX 2.2 PEOPLE AND THE ENVIRONMENT

Asbestos: What Are the Risks?

Asbestos is a commercial term applied to a variety of silicate minerals that readily separate into thin, strong fibres that are highly flexible, heat resistant, and relatively inert. These properties make asbestos a desirable material for the manufacture of a wide variety of products including insulation, fire-proof fabrics, cement, floor tiles, and car brake linings.

The mineral chrysotile, marketed as “white asbestos,” belongs to the serpentine mineral group and accounts for the vast majority of asbestos sold commercially (Figure 2.B). Canada’s only currently mined source of chrysotile is in eastern Quebec in the vicinity of Thetford Mines. Still, Canada is the world’s top exporter and second-largest producer of chrysotile. All other forms of asbestos are amphiboles (defined shortly) and constitute only a minor proportion of asbestos used commercially. The two most common amphibole asbestos minerals are amosite and crocidolite, informally called brown asbestos and blue asbestos, respectively.

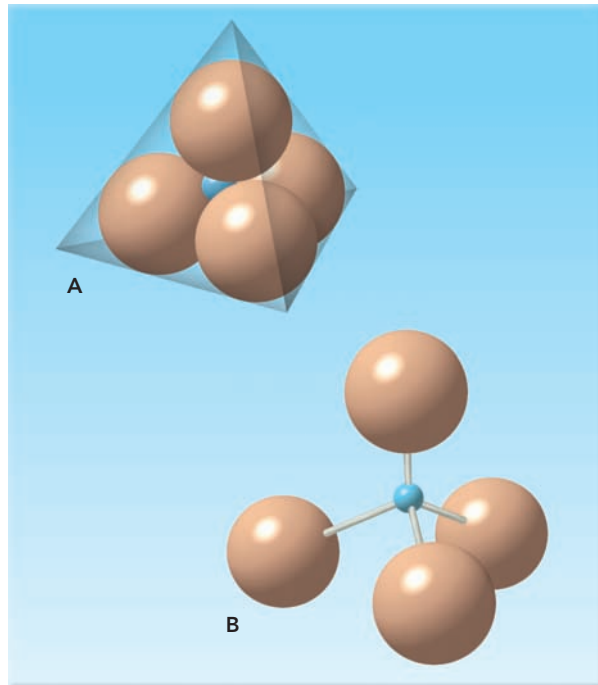
Health concerns about asbestos, raised in the 1980s, stem largely from claims of high death rates attributed to asbestosis (lung scarring from asbestos fibre inhalation), mesothelioma (cancer of the chest and abdominal cavity), and lung cancer among asbestos mine workers. The degree of concern generated by these claims has been well demonstrated by the growth of an entire industry built around asbestos removal from buildings.



◆ **Figure 2.B** Chrysotile asbestos. This sample is a fibrous form of the serpentine group. **Inset:** Thetford Mines, Quebec, the source of all Canadian chrysotile asbestos. (Photo by E. J. Tarbuck)

The stiff, straight fibres of brown and blue (amphibole) asbestos are known to readily pierce, and remain lodged in, the linings of human lungs. The fibres are physically and chemically stable and are not broken down in the human body. These forms of asbestos are therefore a genuine cause for concern. White asbestos, however, being a different mineral, has different properties. The curly fibres of white asbestos are readily expelled from the lungs and, if they are not expelled, can dissolve within a year. Studies conducted on

people living in the Thetford Mines area exposed to high levels of white asbestos dust suggest little, if any, difference in mortality rates from mesothelioma and lung cancer relative to the general public. Despite the fact that more than 90 percent of all asbestos used commercially is white asbestos, a number of countries have banned the use of asbestos in many applications, as the different mineral forms of asbestos are not distinguished. Still, the health hazards of chrysotile at low doses remain controversial.



◆ **Figure 2.21** Two representations of the silicon–oxygen tetrahedron. **A.** The four large spheres represent oxygen ions, and the blue sphere represents a silicon ion. The spheres are drawn in proportion to the radii of the ions. **B.** An expanded view of the tetrahedron using rods to depict the bonds that connect the ions.

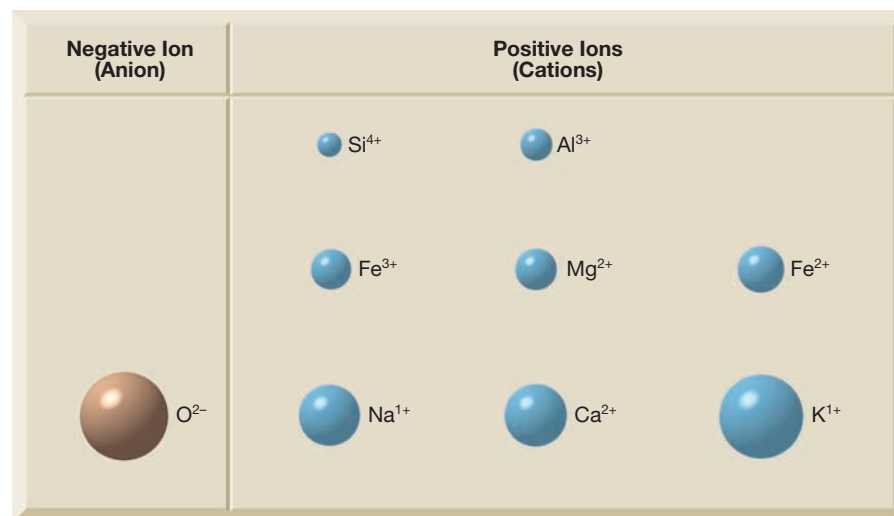
smaller silicon ion with a 4+ charge (Figure 2.21). The silicon–oxygen tetrahedron is therefore a complex ion (SiO_4^{4-}) with an overall charge of 4–.

These tetrahedra join together to become neutral compounds through the addition of cations (Figure 2.22). In this way, a chemically stable structure is produced, consisting of individual tetrahedra linked by cations.

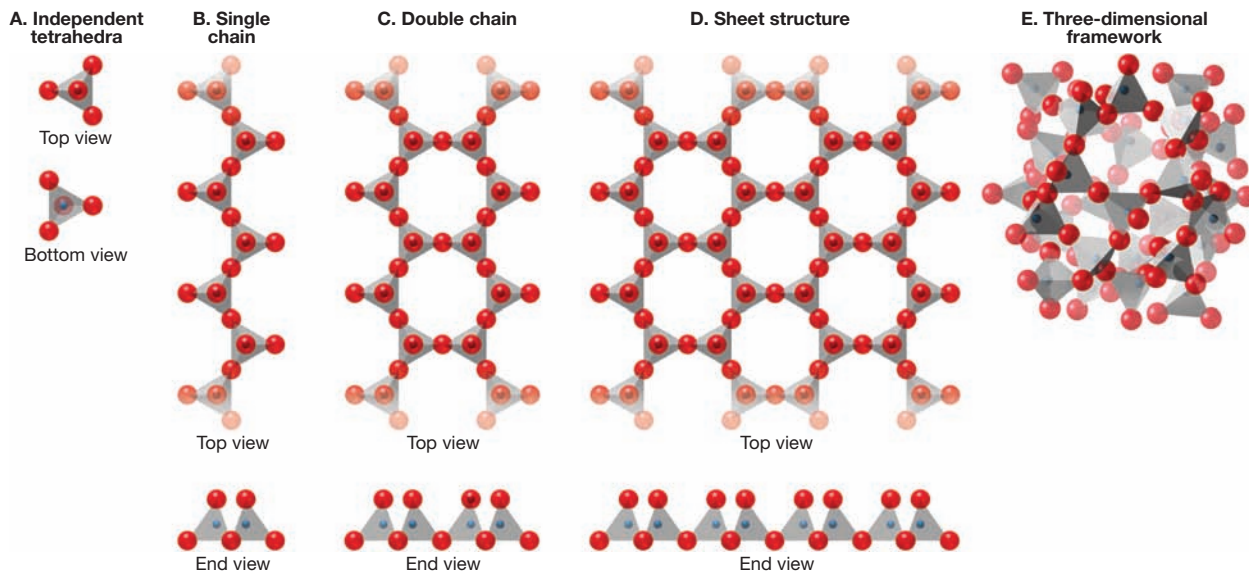
MORE COMPLEX SILICATE STRUCTURES Tetrahedra can link with other tetrahedra (by sharing oxygen ions) to form *single chains*, *double chains*, or *sheet structures* (Figure 2.23). The joining of tetrahedra in each of these configurations results from the sharing of a different number of oxygen atoms between silicon atoms in adjacent tetrahedra.

To understand better how this sharing takes place, select one of the silicon ions (small blue spheres) near the middle of the single-chain structure shown in Figure 2.23A. This silicon ion is completely surrounded by four larger oxygen ions (you are looking *through* one of the four to see the blue silicon ion). Of the four oxygen ions, two are joined to other silicon ions, whereas the other two are not shared this way. *It is the linkage across the shared oxygen ions that joins the tetrahedra as a chain structure.* Now examine a silicon ion near the middle of the sheet structure and count the number of shared and unshared oxygen ions surrounding it (Figure 2.23C). The increase in the degree of sharing accounts for the sheet structure. Other silicate structures exist, and the most common has all of the oxygen ions shared to produce a complex three-dimensional framework.

The ratio of oxygen ions to silicon ions differs in each of the silicate structures. The isolated tetrahedron has four oxygen ions for every silicon ion (Figure 2.23A). In the single chain, the oxygen-to-silicon ratio is 3:1, and in the three-dimensional framework, this ratio is 2:1. As more of the oxygen ions are shared, the percentage of silicon in the structure increases. Silicate minerals are therefore described as having a high or low silicon content based on their ratio of oxygen to silicon. This difference in silicon content is important, as you will see in Chapter 3. Except for quartz (SiO_2) the basic structure (chains, sheets, or three-dimensional frameworks) of most silicate



◆ **Figure 2.22** Relative sizes and electrical charges of ions of the eight most common elements in Earth’s crust. These are the most common ions in rock-forming minerals. Ionic radii are expressed in angstroms.



◆ **Figure 2.23** Five types of silicate structures. **A.** Independent tetrahedra. **B.** Single chains. **C.** Double chains. **D.** Sheet structures. **E.** Three-dimensional framework.

minerals has a net negative charge. Therefore, metal cations are required to bring the overall charge into balance and to serve as the “mortar” that holds these structures together. The cations that most often link silicate structures are iron (Fe^{2+}), magnesium (Mg^{2+}), potassium (K^+), sodium (Na^+), aluminum (Al^{3+}), and calcium (Ca^{2+}). These positively charged ions bond with the unshared oxygen ions that occupy the corners of the silicate tetrahedra.

Figure 2.22 shows that each of these cations has a particular atomic size and a particular charge. Generally, ions of approximately the same size are able to substitute freely for one another. For instance, ions of iron (Fe^{2+}) and magnesium (Mg^{2+}) are nearly the same size and substitute for each other without altering the mineral structure. This also holds true for calcium and sodium ions, which can occupy the same site in a crystalline structure. In addition, aluminum (Al^{3+}) often substitutes for silicon in the silicon–oxygen tetrahedron.

Thus, individual specimens of a particular mineral can contain varying amounts of substituting elements. Such a mineral is expressed by a chemical formula with parentheses to show the variable component. For example, the chemical formula for the mineral olivine, a magnesium-iron silicate, is written as $(\text{Mg},\text{Fe})_2\text{SiO}_4$. The iron (Fe^{2+}) and magnesium (Mg^{2+}) cations in olivine freely substitute for each other. At one extreme, olivine may contain iron without magnesium (Fe_2SiO_4 , or iron silicate), and at the other, iron is lacking (Mg_2SiO_4 , or magnesium silicate). Between these end members, any ratio of iron to magnesium is possible. Thus, olivine, as well as many other silicate

minerals, is actually a *group* of minerals with a range of composition between the two end members.

In certain substitutions, the ions that interchange do not have the same electrical charge. For instance, when calcium (Ca^{2+}) substitutes for sodium (Na^+), the structure gains a positive charge. One way in which this substitution is accomplished, while still maintaining overall electrical neutrality, is the simultaneous substitution of aluminum (Al^{3+}) for silicon (Si^{4+}). This particular double substitution occurs in the mineral plagioclase feldspar, which is a member of the most abundant group of minerals found in Earth’s crust. The end members of this particular feldspar series are a calcium–aluminum silicate (anorthite, $\text{CaAl}_2\text{Si}_2\text{O}_8$), and a sodium–aluminum silicate (albite, $\text{NaAlSi}_3\text{O}_8$).

Figure 2.22 shows that among the major constituents of the silicate minerals, only oxygen is an anion (negatively charged). Because oppositely charged ions attract (and similarly charged ions repel), the chemical bonds that hold silicate structures together form between oxygen and oppositely charged cations. Thus, cations arrange themselves so that they can be as close as possible to oxygen while remaining as far apart from each other as possible. Because of its small size and high charge (+4), the silicon (Si) cation forms the strongest bonds with oxygen. Aluminum (Al) is more strongly bonded to oxygen than are calcium (Ca), magnesium (Mg), iron (Fe), sodium (Na), or potassium (K), but not as strongly as silicon. In many ways, aluminum plays a role similar to that of silicon by being the central ion in the basic tetrahedral structure.

Common Silicate Minerals

The major silicate groups and common examples are given in Figure 2.24. The feldspars (*feld* = field, *spar* = crystal) are by far the most abundant silicate minerals, composing more than 50 percent of Earth's crust. Quartz, the second most abundant mineral in the continental crust, is the only common mineral made completely of silicon and oxygen.

Notice in Figure 2.24 that each mineral group has a particular silicate *structure* and that a relationship exists between the internal structure of a mineral and the *cleavage* it exhibits. Because the silicon–oxygen bonds are strong, silicate minerals tend to cleave between the silicon–oxygen structures rather than across them. For example, the micas have a sheet structure and thus tend to cleave into flat plates (see Figures 2.14 and 2.15). Quartz, which has equally strong silicon–oxygen bonds in all directions, has no cleavage and fractures instead.

Silicate minerals readily form (crystallize) when magma cools and solidifies (as discussed in Chapter 1). This cooling can occur at or near Earth's surface (low temperature and pressure) or at great depths (high temperature and pressure). The environment during crystallization and the chemical composition of the magma determines, to a large degree, which minerals are produced. For example, the silicate mineral olivine crystallizes at high temperatures, whereas quartz crystallizes at much lower temperatures, so the two do not coexist.

In addition, some silicate minerals form at Earth's surface from the weathered products of existing silicate minerals. Still other silicate minerals are formed under the extreme pressures associated with mountain building. Each silicate mineral, therefore, has a structure and a chemical composition that *indicate the conditions under which it formed*. Thus, by carefully examining the mineral constituents of rocks, geologists can often determine the circumstances under which the rocks formed.

We will now examine some of the most common silicate minerals, which we divide into two major categories on the basis of their chemical makeup.



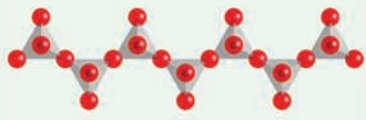
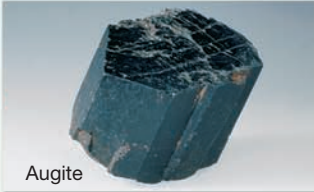
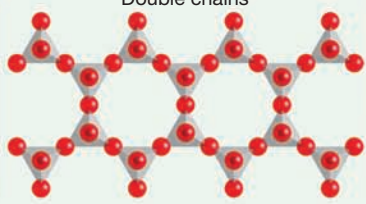

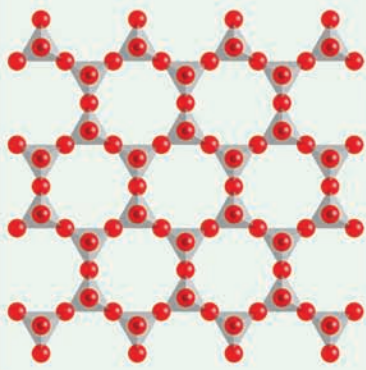


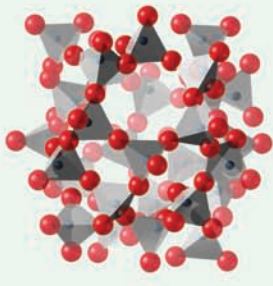


FERROMAGNESIAN (DARK) SILICATES The **dark silicates, or ferromagnesian silicates**, are those minerals containing ions of iron (iron = *ferro*) or magnesium or both in their structure. Because of their iron content, ferromagnesian silicates are dark in colour and have a greater specific gravity, between 3.2 and 3.6, than nonferromagnesian silicates. The most common dark silicate minerals are olivine, the pyroxenes, the amphiboles, the dark mica (biotite), and garnet.

The *olivine* group of high-temperature silicate minerals are black to olive-green and have a glassy lustre and a conchoidal fracture. They are important components of Earth's mantle. The structure of olivine is characterized by individual silica tetrahedra whose oxygens are linked to iron and/or magnesium ions by ionic bonds. Because there are no consistent planes of weakness within its overall structure, olivine lacks a distinct cleavage. Olivine more commonly forms small, rounded crystals than large, angular ones, which is manifested in the granular appearance of most olivine-rich rocks.

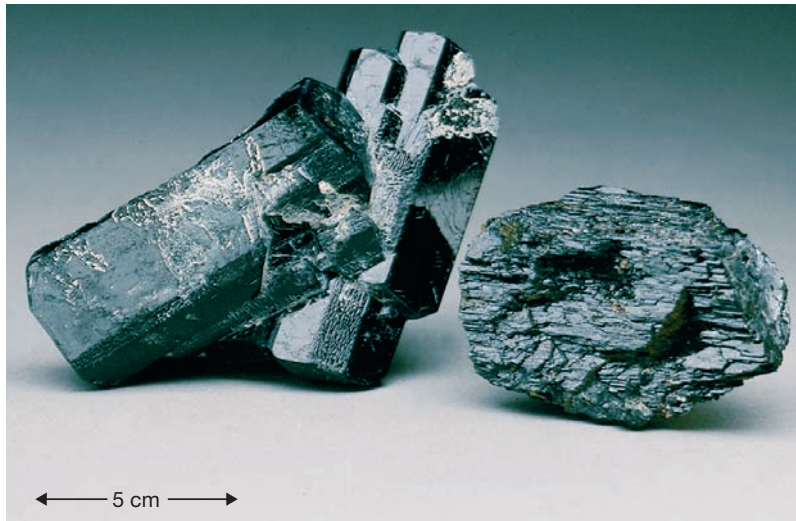
The *pyroxenes* are a group of complex minerals that are important components of dark igneous rocks. The most common member, *augite*, is a dark mineral with two directions of cleavage that meet at a nearly 90-degree angle. Its crystalline structure consists of single chains of tetrahedra bonded by ions of iron and magnesium. Because the silicon–oxygen bonds are stronger than the bonds joining the adjacent silicate chain, augite cleaves parallel to (between) the silicate chains. Augite is one of the dominant minerals in basalt, a common igneous rock of the oceanic crust and volcanic areas on the continents.

Amphibole is a chemically complex group of minerals whose most common member is *hornblende* (Figure 2.25). Hornblende is usually dark green to black and has two directions of cleavage. In contrast to augite, whose two cleavage directions intersect at 90 degrees, hornblende always cleaves at angles of approximately 60 and 120 degrees (Figure 2.26). As in pyroxene minerals, the cleavage angles in amphibole minerals reflect preferential breakage along ionic bonds between the silica chains, which are significantly weaker than the strong covalent bonds within the silica chains themselves. Because the double chains of silica tetrahedra are wider than single chains, the planes of weakness in amphibole minerals intersect at a wider angle (120 degrees) than in pyroxene minerals (90 degrees). Another distinguishing feature of hornblende is that it often forms elongate crystals, in contrast with augite, which tends to form rather stubby, blocky crystals. Hornblende crystals are often visible as dark flecks scattered amongst the lighter-coloured crystals of feldspar and quartz in igneous rocks such as granite.

Biotite is the dark iron-rich member of the mica group. Like other micas, biotite possesses a sheet structure that gives it excellent cleavage in one direction (perfect basal cleavage). Biotite also has a shiny black appearance that helps distinguish it from the other dark ferromagnesian minerals. Like amphibole, biotite is also a common constituent of igneous rocks, including granite.

Mineral/Formula	Cleavage	Silicate Structure	Example
Olivine (Mg, Fe) ₂ SiO ₄	None	Single tetrahedron 	 Olivine
Pyroxene group (Augite) Ca(Mg, Fe, Al)(Al, Si) ₂ O ₆	Two planes at right angles	Single chains 	 Augite
Amphibole group (Hornblende) NaCa ₂ (Mg, Fe, Al) ₅ (Si, Al) ₈ O ₂₂ (OH) ₂	Two planes at 60° and 120°	Double chains 	 Hornblende
Micas	One plane	Sheets 	Biotite K(Mg, Fe) ₃ AlSi ₃ O ₁₀ (OH) ₂  Biotite
			Muscovite KAl ₂ (AlSi ₃ O ₁₀)(OH) ₂  Muscovite
Feldspars	Two planes at 90°	Three-dimensional networks 	Potassium feldspar (Orthoclase) KAlSi ₃ O ₈  Potassium feldspar
			Plagioclase (Ca, Na)(Al, Si)AlSi ₂ O ₈  Quartz
Quartz SiO ₂	None		

◆ **Figure 2.24** Common silicate minerals. Note that the complexity of the silicate structure increases from top to bottom. (Photos by Dennis Tasa and E. J. Tarbuck)



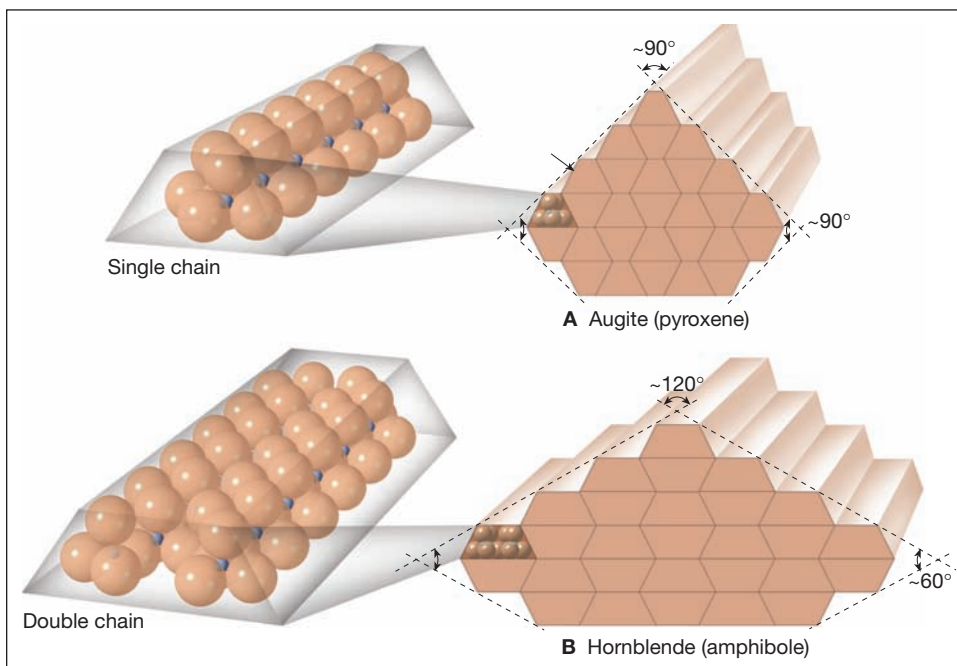
◆ **Figure 2.25** Hornblende variety of amphibole. Hornblende is a common dark silicate mineral having two cleavage directions that intersect at roughly 60° and 120°. (Photo courtesy of E. J. Tarbuck)

Garnet is similar to olivine in that its structure is composed of individual tetrahedra linked by metallic ions. Also like olivine, garnet has a glassy lustre, lacks cleavage, and possesses conchoidal fracture. Although the colours of garnet are varied, this mineral is most commonly brown to deep red. Garnet readily forms equidimensional crystals that are most commonly found in metamorphic rocks (Figure 2.27). When garnets are transparent, they can be used as gemstones.

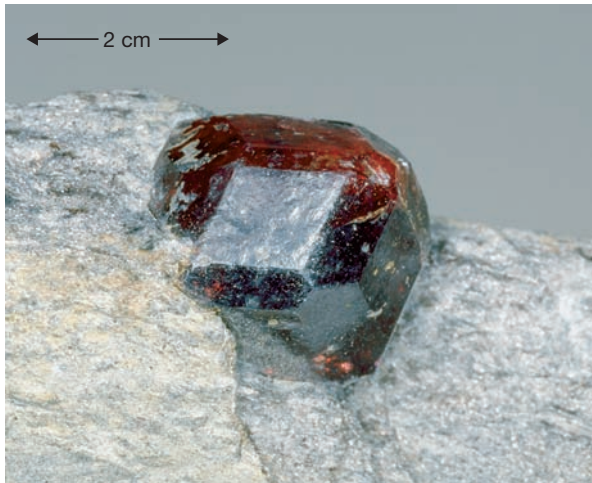
NONFERROMAGNESIAN (LIGHT) SILICATES The light silicates, or nonferromagnesian silicates, are generally light in colour and have a specific

gravity of about 2.7, which is considerably less than the ferromagnesian silicates. As indicated earlier, these differences are mainly attributable to the presence or absence of iron and magnesium. The light silicates contain varying amounts of aluminum, potassium, calcium, and sodium rather than iron and magnesium.

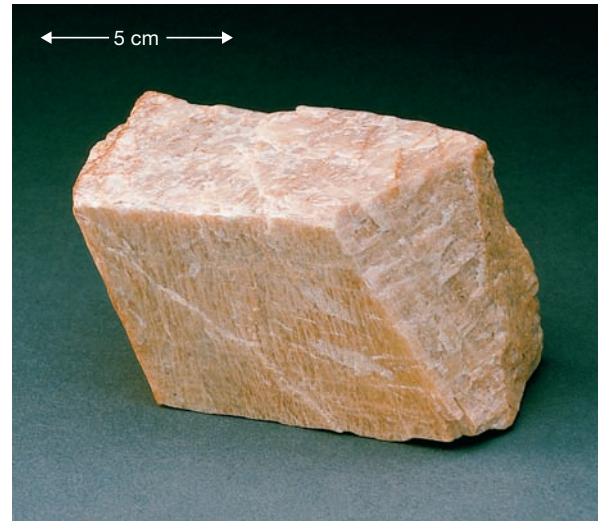
Muscovite is a common member of the mica group. It is light in colour and has a pearly lustre. Like other micas, muscovite has excellent cleavage in one direction (see Figure 2.14). In thin sheets, muscovite is transparent to translucent, a property that accounts for its use in windows during the Middle Ages (called Muscovy glass). Because muscovite is very shiny, it



◆ **Figure 2.26** Cleavage angles for augite and hornblende.



◆ **Figure 2.27** A deep-red garnet crystal embedded in a light-coloured, mica-rich metamorphic rock. (Photo by E. J. Tarbuck)



◆ **Figure 2.28** Sample of the mineral orthoclase feldspar. (Photo by E. J. Tarbuck)

can often be identified by the sparkle it gives a rock. If you have ever looked closely at beach sand, you may have seen the glimmering brilliance of the mica flakes scattered among the other sand grains.

Feldspar, the most common mineral group, can form under a very wide range of temperatures and pressures, a fact that partially accounts for its abundance. All feldspars have similar physical properties: they have two planes of cleavage meeting at or near 90-degree angles, are relatively hard (6 on the Mohs scale), and have a lustre that ranges from glassy to pearly. As one component in a rock, feldspar crystals can be identified by their rectangular shape and rather smooth, shiny faces (Figure 2.28).

Two different feldspar structures exist. *Orthoclase* is a type of feldspar that contains potassium ions in its structure and is therefore often called *potassium feldspar*. The other type, *plagioclase feldspar*, contains both sodium and calcium ions that can freely substitute for each other during crystallization.

Orthoclase feldspar is usually light cream to salmon pink, whereas the plagioclase feldspars tend to range from white to grey to blue-green. However, colour should not be used to distinguish these two types. A more reliable method is to look for fine, parallel, scratch-like lines called *striations* that are commonly present on cleavage planes of plagioclase feldspar but absent in orthoclase feldspar (Figure 2.29).

Quartz is the only common silicate mineral that consists entirely of silicon and oxygen. As such, the term *silica* is applied to quartz, which has the chemical formula SiO_2 . As the structure of quartz contains a ratio of two oxygen ions (O^{2-}) for every silicon ion (Si^{4+}), no other positive ions are needed to attain neutrality.

In quartz a three-dimensional framework is developed mainly through the sharing of oxygens by adjacent silicon ions. The bonds in quartz are primarily the strong silicon–oxygen (covalent) type, rendering it hard and resistant to weathering. As mentioned above, quartz lacks cleavage, but exhibits conchoidal fracture. Pure quartz is clear and colourless and, if allowed to solidify in an open space without interference, can form hexagonal crystals with pyramid-shaped ends (e.g., Figure 2.11B). However, like most other clear minerals, quartz is commonly coloured by the inclusion of various ions (impurities) and often forms without developing good crystal faces. The most common varieties of quartz are milky (white), smoky (grey),



◆ **Figure 2.29** These parallel lines, called striations, are a distinguishing characteristic of the plagioclase feldspars. (Photo by E. J. Tarbuck)

rose (pink), amethyst (purple), and rock crystal (clear) (Figure 2.12).

Clay is a term used to describe a variety of complex minerals that, like the micas, have a sheet structure. The clay minerals are generally very fine-grained and can be studied only microscopically. Most clay minerals originate as products of the chemical weathering of other silicate minerals (mainly feldspars). Thus, clay minerals make up a large percentage of the surface material we call soil. Because of the importance of soil in agriculture, and because of its role as a supporting material for buildings, clay minerals are extremely important to humans.

One of the most common clay minerals is *kaolinite*, which is used in the manufacture of fine chinaware and in the production of high-gloss paper, such as that used in this textbook. Further, some clay minerals absorb large amounts of water, which allows them to swell to several times their normal size. These swelling clays have been used as thickening additives to

milkshakes in fast-food restaurants, as clumping agents in cat litter, and in several other ingenious ways.

Important Nonsilicate Minerals

Other mineral classes are scarce when compared with the silicates, although many are extremely important geologically and economically. Table 2.2 lists examples of several nonsilicate mineral classes of economic value. A discussion of a few of the more common nonsilicate rock-forming minerals follows.

The *carbonate* minerals are much simpler structurally than are the silicates. This mineral class is composed of the carbonate ion (CO_3^{2-}) and one or more kinds of cations. The two most common carbonate minerals are *calcite*, CaCO_3 (calcium carbonate), and *dolomite*, $\text{CaMg}(\text{CO}_3)_2$ (calcium–magnesium carbonate). Because these minerals are similar both physically and chemically, they are difficult to distinguish from each other. Both have a vitreous lustre, a hardness of 3 to 4, and nearly perfect rhombic cleavage

TABLE 2.2 Common Nonsilicate Mineral Classes

Class	Member	Formula	Economic Use
Oxides	Hematite	Fe_2O_3	Ore of iron, pigment
	Magnetite	Fe_3O_4	Ore of iron
	Corundum	Al_2O_3	Gemstone, abrasive
	Ice	H_2O	Solid form of water
	Chromite	FeCr_2O_4	Ore of chromium
	Ilmenite	FeTiO_3	Ore of titanium
Hydroxides	Limonite	$\text{FeO}(\text{OH}) \cdot n\text{H}_2\text{O}$	Ore of iron, pigments
	Bauxite	$\text{Al}(\text{OH})_3 \cdot n\text{H}_2\text{O}$	Ore of aluminum
Sulphides	Galena	PbS	Ore of lead
	Sphalerite	ZnS	Ore of zinc
	Pyrite	FeS_2	Sulphuric acid production
	Chalcopyrite	CuFeS_2	Ore of copper
	Bornite	Cu_5FeS_4	Ore of copper
	Cinnabar	HgS	Ore of mercury
Sulphates	Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	Plaster
	Anhydrite	CaSO_4	Plaster
	Barite	BaSO_4	Drilling mud
Native elements	Gold	Au	Trade, jewellery
	Copper	Cu	Electrical conductor
	Diamond	C	Gemstone, abrasive
	Sulphur	S	Sulpha drugs, chemicals
	Graphite	C	Pencil lead, dry lubricant
	Silver	Ag	Jewellery, photography
	Platinum	Pt	Catalyst
Halides	Halite	NaCl	Common salt
	Fluorite	CaF_2	Component of steelmaking
	Sylvite	KCl	Fertilizer
Carbonates	Calcite	CaCO_3	Portland cement, lime
	Dolomite	$\text{CaMg}(\text{CO}_3)_2$	Portland cement, lime
	Malachite	$\text{Cu}_2\text{CO}_3(\text{OH})_2$	Gemstone
	Azurite	$\text{Cu}_3(\text{CO}_3)_2(\text{OH})_2$	Pigment
Phosphates	Apatite	$\text{Ca}_5(\text{PO}_4)_3(\text{F}, \text{Cl}, \text{OH})$	Fertilizer
	Turquoise	$\text{CuAl}_6(\text{PO}_4)_4(\text{OH})_8$	Gemstone



◆ **Figure 2.30** Thick beds of potash (potassium-rich salt deposit) in an underground mine in Saskatchewan. (Photo by Jisuo Jin)

(in three directions, not at 90 degrees; see Figure 2.15). They can, however, be distinguished by using dilute hydrochloric acid. As noted earlier, calcite reacts vigorously with this acid; dolomite reacts much more slowly. Calcite and dolomite are usually found together as the primary constituents in the sedimentary rocks limestone (in which calcite dominates) and dolostone (in which dolomite dominates). Limestone has numerous economic uses as road aggregate, building stone, and the main ingredient in portland cement.

Three other nonsilicate minerals found in sedimentary rocks are *halite*, *sylvite*, and *gypsum*. These minerals are commonly found in thick layers, which are the last vestiges of ancient seas and saline lakes that have long since evaporated (Figure 2.30). Like limestone, they are important nonmetallic resources. Halite is the mineral name for common table salt (NaCl), whereas sylvite (KCl) is the principal mineral of potash used in fertilizers. Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), calcium sulphate with water bound

into the structure, is the mineral from which plaster and other similar building materials are made.

A number of other minerals are prized for their economic value (see Table 2.2 and Box 2.2). Included in this category are the ores of metals, such as hematite (iron), sphalerite (zinc), and galena (lead); the native (free-occurring, not in compounds) elements, including gold, silver, and carbon (diamonds); and a host of others, such as fluorite, corundum, and uraninite (a uranium source).*

In the chapters that follow we will see that minerals combine under different pressure and temperature conditions in the rock cycle (see Chapter 1) to form various rocks. Some minerals are found together because they are formed under similar conditions they have similar chemical makeup.

*For more on the economic significance of these and other minerals, see Chapter 20.

BOX 2.3 UNDERSTANDING EARTH

Gemstones



Precious stones have been prized since antiquity. But misinformation abounds regarding gems and their mineral makeup. This stems partly from the ancient practice of grouping precious stones by colour rather than by mineral makeup. For example,

rubies and red *spinels* are very similar in colour, but they are completely different minerals. Classifying by colour led to the more common spinels being passed off as rubies to royalty. Even today, with modern identification techniques, common *yellow*

quartz is sometimes sold as the more valuable gemstone *topaz*.

Naming Gemstones

Most precious stones have common names that are different from their parent mineral. For example, *sapphire*

is one of two names given to the mineral *corundum*. Minute amounts of foreign elements can produce vivid sapphires of nearly every colour (Figure 2.C). Traces of titanium and iron in corundum produce the most-prized: blue sapphires. When corundum contains a sufficient quantity of chromium, it exhibits a brilliant red colour, and the gemstone is called *ruby*. If a specimen is not suitable as a gem, it simply goes by the mineral name *corundum*. Because of its hardness, corundum that is not of gem quality is often crushed and sold as an abrasive. Most natural rubies and sapphires have been heated and recrystallized to enhance their clarity and colour.

To summarize, when corundum exhibits a red hue, it is called *ruby*, but if it exhibits any other colour, the gemstone is called *sapphire*. Whereas corundum is the base mineral for two gemstones, quartz is the parent of more than a dozen gems. Table 2.A lists some well-known gemstones and their parent minerals.

What Constitutes a Gemstone?

When found in their natural state, most gemstones are dull and would be passed over by most people as just another rock. Gems must be cut and polished by experienced professionals before their true beauty is displayed (Figure 2.C). Only those mineral specimens that are of such quality that they can command a price in excess of the cost of processing are considered gemstones.

Gemstones can be divided into two categories: precious and semiprecious. A *precious* gemstone has beauty, durability, size, and rarity, whereas a *semiprecious* gemstone generally has only one or two of these qualities. The gemstones traditionally held in highest esteem are diamonds, rubies, sapphires, emeralds, and some varieties of opal (Table 2.A). All other gemstones are classified as semiprecious. However, large high-quality specimens of semiprecious stones often command a very high price.

Today translucent stones with evenly tinted colours are preferred. The most favoured hues are red, blue, green, purple, rose, and yellow.



◆ **Figure 2.C** Australian sapphires showing variation in cuts and colours. (Photo by Fred Ward, Black Star)

TABLE 2.A Important Gemstones

Gemstone	Mineral Name	Prized Hues
Precious		
Diamond	Diamond	Colourless, yellows
Emerald	Beryl	Greens
Opal	Opal	Brilliant hues
Ruby	Corundum	Reds
Sapphire	Corundum	Blues
Semiprecious		
Alexandrite	Chrysoberyl	Variable
Amethyst	Quartz	Purples
Cat's-eye	Chrysoberyl	Yellows
Chalcedony	Quartz (agate)	Banded
Citrine	Quartz	Yellows
Garnet	Garnet	Reds, greens
Jade	Jadeite or nephrite	Greens
Moonstone	Feldspar	Transparent blues
Peridot	Olivine	Olive greens
Smoky quartz	Quartz	Browns
Spinel	Spinel	Reds
Topaz	Topaz	Purples, reds
Tourmaline	Tourmaline	Reds, blue-greens
Turquoise	Turquoise	Blues
Zircon	Zircon	Reds

The most-prized stones are pigeon-blood rubies, blue sapphires, grass-green emeralds, and canary-yellow diamonds. Colourless gemstones are generally less than desirable, except for diamonds that display flashes of colour known as fire.

The durability of a gemstone depends on its hardness; that is, its resistance to abrasion by objects normally encountered in everyday living. For good durability, gemstones should be as hard as or harder than quartz as defined by the Mohs scale of hardness.

One notable exception is opal, which is comparatively soft (hardness of 5 to 6.5) and brittle. Opal's esteem comes from its "fire," which is a display of a variety of brilliant colours, including greens, blues, and reds.

It seems to be human nature to treasure what is rare. In the case of gemstones, large high-quality specimens are much rarer than smaller stones. Thus, large rubies, diamonds, and emeralds, which are rare in addition to being beautiful and durable, command the very highest prices.

CHAPTER SUMMARY

- A mineral is a natural, usually inorganic solid with a chemical structure that gives it unique physical properties. Most rocks are aggregates of minerals. Building blocks of minerals are elements. An atom is the smallest particle having characteristics of an element. Each atom has a nucleus containing protons (positive charges) and neutrons (no charges). Orbiting the nucleus are electrons (negative charges).
- In ionic bonds electrons are transferred between atoms, resulting in net positive or negative charged ions. In covalent bonds atoms share electrons. Mineral properties include crystal habit, lustre, colour, streak, hardness, cleavage, fracture, specific gravity, and others used to tell minerals apart.
- Oxygen, silicon, aluminum, iron, calcium, sodium, potassium, and magnesium make up most of the common minerals and over 98 percent of continental crust.
- The most common mineral class is the silicates, all of which contain silicon–oxygen tetrahedra. Tetrahedra can be linked in chains (pyroxene, amphibole), sheets (micas), or networks (feldspar, quartz) bonded by iron, magnesium, potassium, sodium, aluminum, and calcium cations.
- Common nonsilicate classes include carbonates (e.g., calcite), oxides (hematite), sulphides (sphalerite), sulphates (gypsum), halides (halite), and native elements (gold).



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REVIEW QUESTIONS

1. List the three main particles of an atom and explain how they differ from one another. What are the characteristics a material must have in order to be considered a true mineral?
2. Based on the criteria outlined in this chapter, could ice be considered a mineral? Discuss.
3. What is the difference between a mineral and a rock?
4. Explain the difference between ionic and covalent bonding.
5. What is the difference between silicon, silica, and silicate?
6. What is the difference between cleavage and fracture?
7. How would you determine whether a flat surface on a mineral crystal is a crystal face or a cleavage plane?
8. If you were given a mineral specimen of unknown hardness and a full set of minerals (and other materials) of known hardness, how would you determine the hardness of the “unknown” mineral using Mohs scale as a guide?
9. What are the main types of silicate structures (i.e., the manner in which silica units are arranged and/or linked within mineral crystals) represented in 1) the ferromagnesian mineral groups (olivine, pyroxene, amphibole, and biotite mica), 2) the feldspars, and 3) quartz.