CHAPTER 4

Minerals

BIGIDEA Minerals are an integral part of daily life.

SECTIONS

1 What is a mineral?

2 Types of Minerals

LaunchLAB

iLab Station

What shapes do minerals form?

Although there are thousands of minerals in Earth's crust, each type of mineral has unique characteristics. These characteristics are clues to a mineral's composition and to the way it formed. Physical properties can also be used to distinguish one type of mineral from another. Examine different crystal shapes in this lab.

FOLDABLES® Study Organizer

Mineral Identification

Make a layered-look book and label the tabs with the names of the tests used to identify minerals. Use it to organize your notes on mineral identification.

Go **online!**
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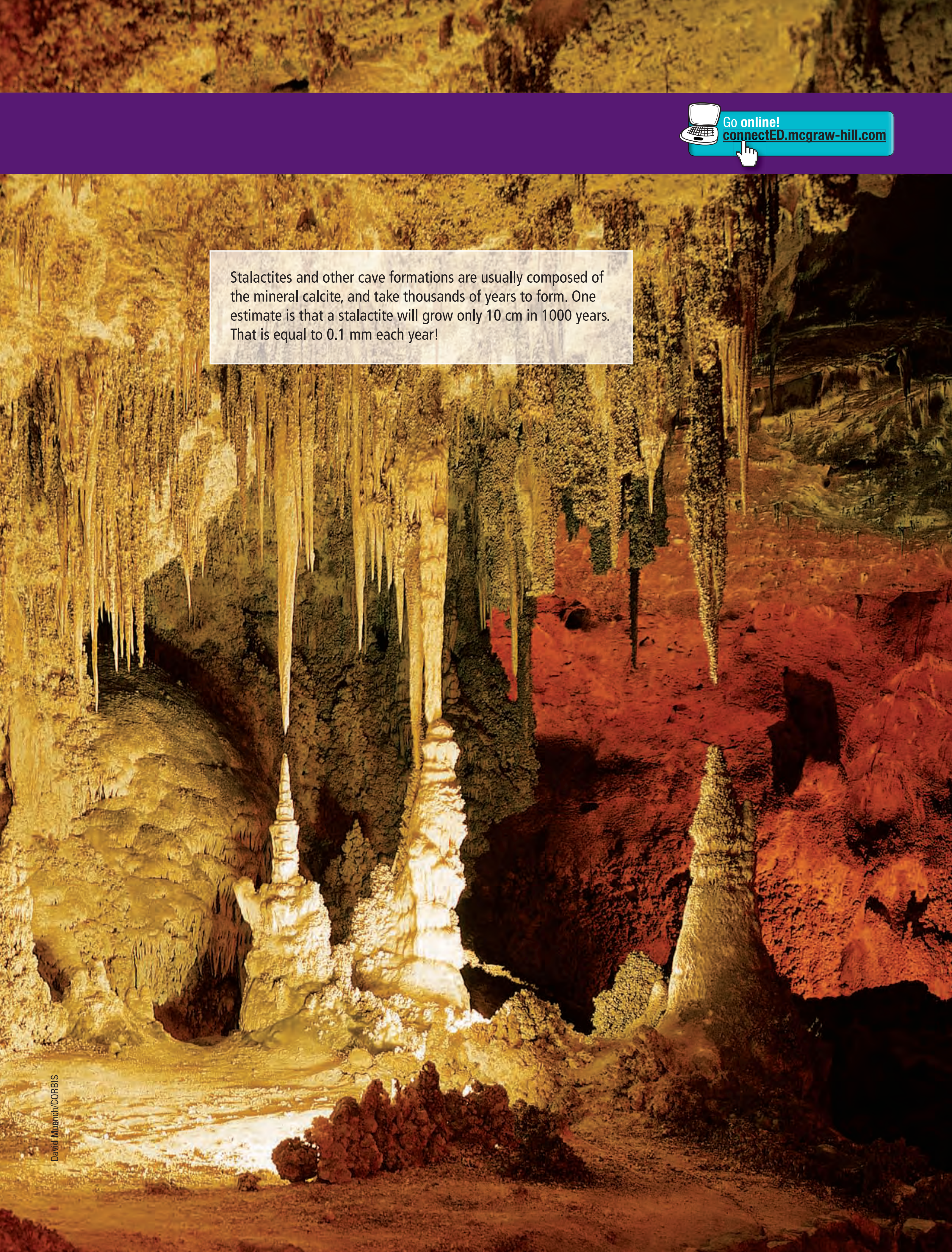


Stalactites and other cave formations are usually composed of the mineral calcite, and take thousands of years to form. One estimate is that a stalactite will grow only 10 cm in 1000 years. That is equal to 0.1 mm each year!

SECTION 1

What is a mineral?

MAINIDEA **Minerals are naturally occurring, solid, inorganic compounds or elements.**

Essential Questions

- How are minerals defined?
- How do minerals form?
- How are minerals classified?

Review Vocabulary

element: a pure substance that cannot be broken down into simpler substances by chemical or physical means

New Vocabulary

mineral
crystal
luster
hardness
cleavage
fracture
streak
specific gravity

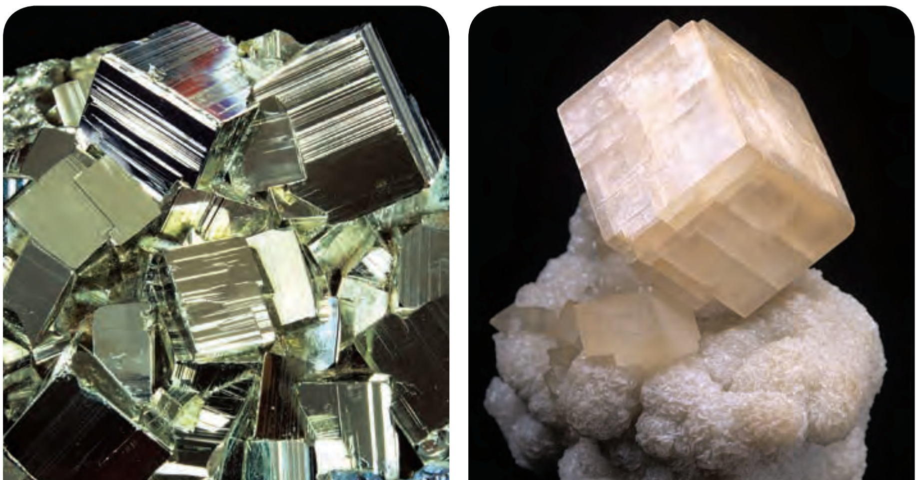
EARTH SCIENCE 4 YOU **Look around your classroom. The metal in your desk, the graphite in your pencil, and the glass in the windows are just three examples of how modern humans use products made from minerals.**

Mineral Characteristics

Earth's crust is composed of about 3000 minerals. Minerals play important roles in forming rocks and in shaping Earth's surface. A select few have helped shape civilization. For example, great progress in prehistory was made when early humans began making tools from iron.

A **mineral** is a naturally occurring, inorganic solid, with a specific chemical composition and a definite crystalline structure. This crystalline structure is often exhibited by the crystal shape itself. Examples of mineral crystal shapes are shown in **Figure 1.**

Naturally occurring and inorganic Minerals are naturally occurring, meaning that they are formed by natural processes. Such processes will be discussed later in this section. Thus, synthetic diamonds and other substances developed in labs are not minerals. All minerals are inorganic. They are not alive and never were alive. Based on these criteria, salt is a mineral, but sugar, which is harvested from plants, is not. What about coal? According to the scientific definition of minerals, coal is not a mineral because millions of years ago, it formed from organic materials.



Pyrite Calcite

Figure 1 The shapes of these mineral crystals reflect the internal arrangements of their atoms.

(l)Martin Bond/Photo Researchers, (r)Mark A. Schneider/Visuals Unlimited

Definite crystalline structure The atoms in minerals are arranged in regular geometric patterns that are repeated. This regular pattern results in the formation of a crystal. A **crystal** is a solid in which the atoms are arranged in repeating patterns. Sometimes, a mineral will form in an open space and grow into one large crystal. The well-defined crystal shapes shown in **Figure 1** are rare. More commonly, the internal atomic arrangement of a mineral is not apparent because the mineral formed in a restricted space. **Figure 2** shows a sample of quartz that formed in a restricted space.

☑ READING CHECK **Describe** the atomic arrangement of a crystal.

■ **Figure 2** This piece of quartz most likely formed in a restricted space, such as within a crack in a rock.

Solids with specific compositions The fourth characteristic of minerals is that they are solids. Recall that solids have definite shapes and volumes, while liquids and gases do not. Because of this, no gas or liquid can be considered a mineral

Each type of mineral has a chemical composition unique to that mineral. This composition might be specific, or it might vary within a set range of compositions. A few minerals, such as copper, silver, and sulfur, are composed of single elements. The vast majority, however, are made from compounds. The mineral quartz (SiO_2), for example, is a combination of two atoms of oxygen and one atom of silicon. Although other minerals might contain silicon and oxygen, the arrangement and proportion of these elements in quartz are unique to quartz.

VOCABULARY

ACADEMIC VOCABULARY

Restricted
small space; to have limits
The room was so small that it felt very restricted.

Quartz

Aquamarine

(t)Biophoto Associates/Photo Researchers, (bl)GC Minerals/Alamy Images, (br)Lawrence Lawry/Photo Researchers

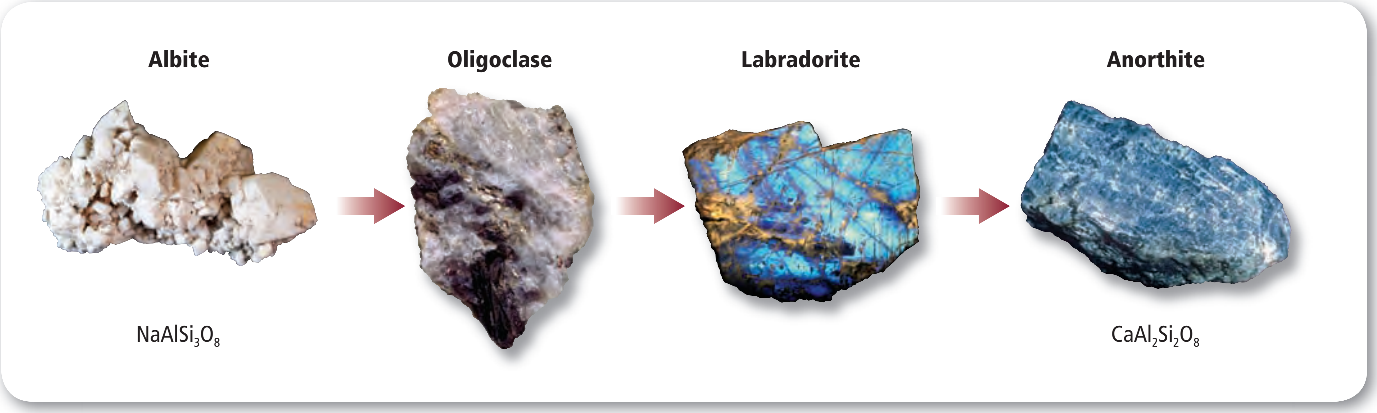


Figure 3 The mineral albite is a sodium-rich feldspar, while anorthite is calcium-rich. Oligoclase and labradorite contain both sodium and calcium in varying compositions.

Variations in Composition In some minerals, chemical composition can vary slightly depending on the temperature at which the mineral crystallizes. The plagioclase feldspar, shown in **Figure 3,** ranges from sodium-rich albite (AHL bite) at low temperatures to calcium-rich anorthite (uh NOR thite) at high temperatures. The difference in the mineral's appearance is due to a slight change in the chemical composition and a difference in growth pattern as the temperature changes. At intermediate temperatures, both calcium and sodium are incorporated into the crystal structure. This builds up alternating layers that allow light to refract or scatter, producing a range of colors, as shown in the labradorite in **Figure 3.**

Rock-Forming Minerals

Although about 3000 minerals occur in Earth's crust, only about 30 of these are common. Eight to ten of these minerals are referred to as rock-forming minerals because they make up most of the rocks in Earth's crust. They are primarily composed of the eight most common elements in Earth's crust. This is illustrated in **Table 1.**

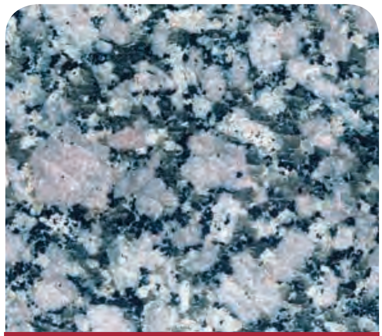
Table 1 Most Common Rock-Forming Minerals

Quartz	Feldspar	Mica	Pyroxene*
SiO_2	$NaAlSi_3O_8 - CaAl_2Si_2O_8$ $KAlSi_3O_8$	$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$ $KAl_2(AlSi_3O_{10})(OH)_2$	$MgSiO_3$ $Ca(Mg,Fe)Si_2O_6$ $NaAlSi_2O_6$
Amphibole*	**Olivine**	**Garnet***	**Calcite**
$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$ $Fe_7Si_8O_{22}(OH)_2$	$(Mg,Fe)_2SiO_4$	$Mg_3Al_2Si_3O_{12}$ $Fe_3Al_2Si_3O_{12}$ $Ca_3Al_2Si_3O_{12}$	$CaCO_3$

*representative mineral compositions

Minerals from magma Molten material that forms and accumulates below Earth's surface is called magma. Magma is less dense than the surrounding solid rock, so it can rise upward into cooler layers of Earth's interior. Here, the magma cools and crystallizes. The type and number of elements present in the magma determine which minerals will form. The rate at which the magma cools determines the size of the mineral crystals. If the magma cools slowly within Earth's heated interior, the atoms have time to arrange themselves into large crystals. If the magma reaches Earth's surface, comes in contact with air or water, and cools quickly, the atoms do not have time to arrange themselves into large crystals. Thus, small crystals form from rapidly cooling magma, and large crystals form from slowly cooling magma. The mineral crystals in the granite shown in **Figure 4** are the result of slowly cooling magma.

☑ READING CHECK **Explain** how contact with water affects crystal size.



Granite

Rock salt

■ **Figure 4** The crystals in these two samples formed in different ways.
Describe *the differences you see in these rock samples.*

Minerals from solutions Minerals are often dissolved in water. For example, the salts that are dissolved in ocean water make it salty. When a liquid becomes full of a dissolved substance and it can dissolve no more of that substance, the liquid is saturated. If more solute is added, the solution is called supersaturated and conditions are right for minerals to form. At this point, individual atoms bond together and mineral crystals precipitate, which means that they form into solids from the solution.

Minerals also crystallize when the solution in which they are dissolved evaporates. You might have experienced this if you have ever gone swimming in the ocean. As the water evaporated off your skin, the salts were left behind as mineral crystals. Minerals that form from the evaporation of liquid are called evaporites. The rock salt in **Figure 4** was formed from evaporation. **Figure 5** shows Mammoth Hot Springs, a large evaporite complex in Yellowstone National Park.

■ **Figure 5** This large complex of evaporite minerals is in Yellowstone National Park. The variation in color is the result of the variety of elements that are dissolved in the water.

Identifying Minerals

Geologists rely on several simple tests to identify minerals. These tests are based on a mineral's physical and chemical properties: crystal form, luster, hardness, cleavage, fracture, streak, color, texture, density, specific gravity, and special properties. As you will learn in the GeoLab at the end of this chapter, it is usually best to use a combination of tests instead of just one to identify minerals.

Crystal form Some minerals form such distinct crystal shapes that they are immediately recognizable. Halite—common table salt—always forms perfect cubes. Quartz crystals, with their double-pointed ends and six-sided crystals, are also readily recognized. However, as you learned earlier in this section, perfect crystals are not always formed, so identification based only on crystal form is rare.

Luster The way that a mineral reflects light from its surface is called **luster.** There are two types of luster—metallic luster and nonmetallic luster. Silver, gold, copper, and galena have shiny surfaces that reflect light, like the chrome trim on cars. Thus, they are said to have a metallic luster. Not all metallic minerals are metals. If their surfaces have shiny appearances like metals, they are considered to have a metallic luster. Sphalerite, for example, is a mineral with a metallic luster that is not a metal.

Minerals with nonmetallic lusters, such as calcite, gypsum, sulfur, and quartz, do not shine like metals. Nonmetallic lusters might be described as dull, pearly, waxy, silky, or earthy. Differences in luster, shown in **Figure 6,** are caused by differences in the chemical compositions of minerals. Describing the luster of nonmetallic minerals is a subjective process. For example, a mineral that appears waxy to one person might not appear waxy to another. Using luster to identify a mineral should usually be used in combination with other physical characteristics.

☑ READING CHECK **Define** the term *luster.*

CAREERS IN EARTH SCIENCE

Lapidary A lapidary is someone who cuts, polishes, and engraves precious stones. He or she studies minerals and their properties in order to know which minerals are the best for certain projects.

WebQuest

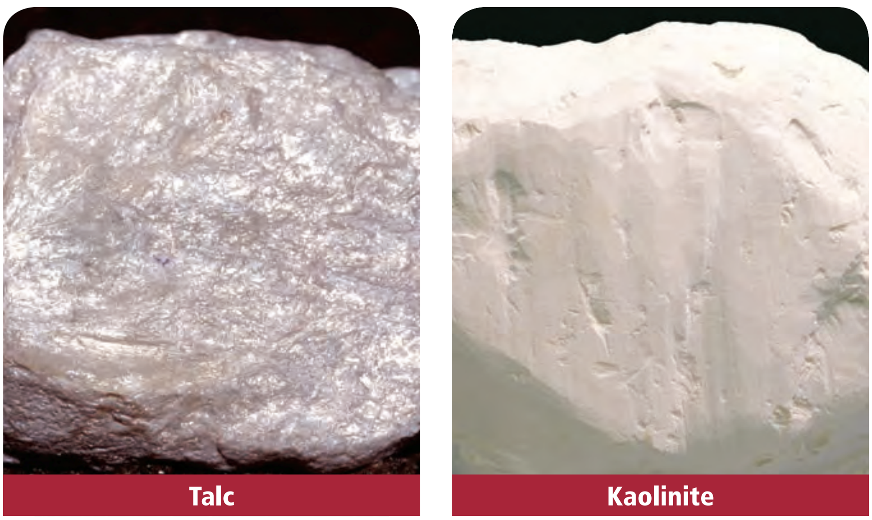


Figure 6 The flaky and shiny nature of talc gives it a pearly luster. Another white mineral, kaolinite, contrasts sharply with its dull, earthy luster.

(l)Andrew J. Martinez/Photo Researchers, (r)Doug Sherman/Geofile

Explore **Mohs scale with an interactive table.** Concepts In Motion

Table 2 Mohs Scale of Hardness

Mineral	Hardness	Hardness of Common Objects
Diamond	10	
Corundum	9	
Topaz	8	
Quartz	7	streak plate = 7
Feldspar	6	steel file = 6.5
Apatite	5	glass = 5.5
Fluorite	4	iron nail = 4.5
Calcite	3	piece of copper = 3.5
Gypsum	2	fingernail = 2.5
Talc	1	

Hardness One of the most useful and reliable tests for identifying minerals is hardness. **Hardness** is a measure of how easily a mineral can be scratched. German geologist Friedrich Mohs developed a scale by which an unknown mineral's hardness can be compared to the known hardness of ten minerals. The minerals in the Mohs scale of mineral hardness were selected because they are easily recognized and, with the exception of diamond, readily found in nature.

READING CHECK **Explain** what hardness measures.

Talc is one of the softest minerals and can be scratched by a fingernail; therefore, talc represents 1 on the Mohs scale of hardness. In contrast, diamond is so hard that it can be used as a sharpener and cutting tool, so diamond represents 10 on the Mohs scale of hardness. The scale, shown in **Table 2,** is used in the following way: a mineral that can be scratched by your fingernail has a hardness less than 2.5. A mineral that cannot be scratched by your fingernail and cannot scratch glass has a hardness value between 5.5 and 2.5. Finally, a mineral that scratches glass has a hardness greater than 5.5. Using other common objects, such as those listed in the table, can help you determine a more precise hardness and provide you with more information with which to identify an unknown mineral. Sometimes more than one mineral is present in a sample. If this is the case, it is a good idea to test more than one area of the sample. This way, you can be sure that you are testing the hardness of the mineral you are studying. **Figure 7** shows two minerals that have different hardness values.

Figure 7 The mineral on top can be scratched with a fingernail. The mineral on the bottom easily scratches glass.
Determine *Which mineral has greater hardness?*

Matt Meadows

Figure 8 Halite has perfect cleavage in three directions; it breaks apart into pieces that have 90° angles. The strong bonds in quartz prevent cleavage from forming. Conchoidal fractures are characteristic of microcrystalline minerals such as flint.

Cleavage and fracture Atomic arrangement also determines how a mineral will break. Minerals break along planes where atomic bonding is weak. A mineral that splits relatively easily and evenly along one or more flat planes is said to have **cleavage.** To identify a mineral according to its cleavage, geologists count the number of cleaved planes and study the angle or angles between them. For example, mica has perfect cleavage in one direction. It breaks in sheets because of weak atomic bonds. Halite, shown in **Figure 8,** has cubic cleavage, which means that it breaks in three directions along planes of weak atomic attraction. Quartz and flint do not have natural planes of separation. They fracture instead of cleave.

MiniLAB

iLab Station

Recognize Cleavage and Fracture

How is cleavage used? Cleavage forms when a mineral breaks along a plane of weakly bonded atoms. If a mineral has no cleavage, it exhibits fracture. Recognizing the presence or absence of cleavage and determining the number of cleavage planes is a reliable method of identifying minerals.

Procedure

Part 1

1. Read and complete the lab safety form.
2. Obtain five **mineral samples** from your teacher. Separate them into two sets—those with cleavage and those without cleavage.
3. Arrange the minerals that have cleavage in order from fewest to most cleavage planes. How many cleavage planes does each sample have? Identify these minerals if you can.
4. Examine the samples that have no cleavage. Describe their surfaces. Identify these minerals if you can.

Part 2

5. Obtain two more samples from your teacher. Are these the same mineral? How can you tell?
6. Use a **protractor** to measure the cleavage plane angles of both minerals. Record your measurements.

Analysis

1. **Record** the number of cleavage planes or presence of fracture for all seven samples.
2. **Compare** the cleavage plane angles for Samples 6 and 7. What do they tell you about the mineral samples?
3. **Predict** the shape each mineral would exhibit if you were to hit each one with a hammer.

Quartz, shown in **Figure 8,** breaks unevenly along jagged edges because of its tightly bonded atoms. Minerals that break with rough or jagged edges are said to have **fracture.** Flint, jasper, and chalcedony (kal SEH duh nee) (microcrystalline forms of quartz) exhibit a unique fracture with arclike patterns resembling clamshells, also shown in **Figure 8.** This fracture is called conchoidal (kahn KOY duhl) fracture and is diagnostic in identifying the rocks and minerals that exhibit it.

Streak A mineral rubbed across an unglazed porcelain plate will sometimes leave a colored powdered streak on the surface of the plate. **Streak** is the color of a mineral when it is broken up and powdered. The streak of a nonmetallic mineral is usually white. Streak is most useful in identifying metallic minerals.

Sometimes, a metallic mineral's streak does not match its external color, as shown in **Figure 9.** For example, the mineral hematite occurs in two different forms, resulting in two distinctly different appearances. Hematite that forms from weathering and exposure to air and water is a rusty red color and has an earthy feel. Hematite that forms from crystallization of magma can be silver and metallic in appearance. However, both forms make a reddish-brown streak when tested. The streak test can be used only on minerals that are softer than a porcelain plate. This is another reason why streak cannot be used to identify all minerals.

☑ READING CHECK **Explain** which type of mineral can be identified using streak.

Color One of the most noticeable characteristics of a mineral is its color. Color is sometimes caused by the presence of trace elements or compounds within a mineral. For example, quartz occurs in a variety of colors, as shown in **Figure 10.** These different colors are the result of different trace elements in the quartz samples. Red jasper, purple amethyst, and orange citrine contain different amounts and forms of iron. Rose quartz contains manganese or titanium. However, the appearance of milky quartz is caused by the numerous bubbles of gas and liquid trapped within the crystal. In general, color is one of the least reliable clues of a mineral's identity.

■ **Figure 9** Despite the fact that these pieces of hematite appear remarkably different, their chemical compositions are the same. Thus, the streak that each makes is the same color.

FOLDABLES®
Incorporate information from this section into your Foldable.

■ **Figure 10** These varieties of quartz all contain silicon and oxygen. Trace elements determine their colors.

Red jasper

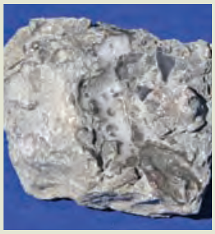
Amethyst

Citrine

Rose quartz

Explore **minerals with an interactive table.** **Concepts In Motion**

Table 3 Special Properties of Minerals

Property	**Double refraction** occurs when a ray of light passes through the mineral and is split into two rays.	**Effervescence** occurs when reaction with hydrochloric acid causes calcite to fizz.	**Magnetism** occurs between minerals that contain iron; only magnetite and pyrrhotite are strongly magnetic.	**Iridescence**—a play of colors, caused by the bending of light rays.	**Fluorescence** occurs when some minerals are exposed to ultraviolet light, which causes them to glow in the dark.
Mineral	Calcite—Variety Iceland Spar	Calcite	Magnetite Pyrrhotite	Labradorite	Fluorite Calcite
Example					

Special properties Several special properties of minerals can also be used for identification purposes. Some of these properties are magnetism, iridescence, double refraction, effervescence with hydrochloric acid, and fluorescence, shown in **Table 3**. For example, Iceland spar is a form of calcite that exhibits double refraction. The arrangement of atoms in this type of calcite causes light to be bent in two directions when it passes through the mineral. The refraction of the single ray of light into two rays creates the appearance of two images.

Data Analysis LAB

Based on Real Data*

Make and Use a Table

What information should you include in a mineral identification chart?

Mineral Identification Chart			
Mineral Color	**Streak**	**Hard-ness**	**Breakage Pattern**
copper red		3	hackly, fracture
	red or reddish brown	6	irregular fracture
pale to golden yellow	yellow		
	colorless	7.5	conchoidal fracture
gray, green or white			two cleavage planes

Analysis

1. Copy the data table and use the *Reference Handbook* to complete the table.
2. Expand the table to include the names of the minerals, other properties, and uses.

Think Critically

3. **Determine** which of these minerals will scratch glass? Explain.
4. **Identify** which of these minerals might be present in both a painting and your desk.
5. **Identify** any other information you could include in the table.

*Data obtained from: Klein, C. 2002. *The Manual of Mineral Science.*

Texture Texture describes how a mineral feels to the touch. This, like luster, is subjective. Therefore, texture is often used in combination with other tests to identify a mineral. The texture of a mineral might be described as smooth, rough, ragged, greasy, or soapy. For example, fluorite, shown in **Figure 11,** has a smooth texture, while the texture of talc, shown in **Figure 6,** is greasy.

■ **Figure 11** Textures are interpreted differently by different people. The texture of this fluorite is usually described as smooth.

Density and specific gravity Sometimes, two minerals of the same size have different weights. Differences in weight are the result of differences in density, which is defined as mass per unit of volume. Density is expressed as follows.

$$D = \frac{M}{V}$$

In this equation, D = density, M = mass and V = volume. For example, pyrite has a density of 5.2 g/cm^3, and gold has a density of 19.3 g/cm^3. If you had a sample of gold and a sample of pyrite of the same size, the gold would have greater weight because it is denser.

Density reflects the atomic mass and structure of a mineral. Because density is not dependent on the size or shape of a mineral, it is a useful identification tool. Often, however, differences in density are too small to be distinguished by lifting different minerals. Thus, for accurate mineral identification, density must be measured. The most common measure of density used by geologists is **specific gravity,** which is the ratio of the mass of a substance to the mass of an equal volume of water at 4°C. For example, the specific gravity of pyrite is 5.2. The specific gravity of pure gold is 19.3.

SECTION 1 REVIEW

Section Self-Check

Section Summary

- A mineral is a naturally occurring, inorganic solid with a specific chemical composition and a definite crystalline structure.
- A crystal is a solid in which the atoms are arranged in repeating patterns.
- Minerals form from magma, supersaturated solutions, or evaporation of solutions in which they are dissolved.
- Minerals can be identified based on physical and chemical properties.
- The most reliable way to identify a mineral is by using a combination of several tests.

Understand Main Ideas

1. **MAIN**IDEA **List** two reasons why petroleum is not a mineral.
2. **Define** *naturally occurring* in terms of mineral formation.
3. **Contrast** the formation of minerals from magma and their formation from solution.
4. **Differentiate** between subjective and objective mineral properties.

Think Critically

5. **Develop** a plan to test the hardness of a sample of feldspar using the following items: glass plate, copper penny, and streak plate.
6. **Predict** the success of a lab test in which students plan to compare the streak colors of fluorite, quartz, and feldspar.

MATH IN Earth Science

7. Calculate the volume of a 5-g sample of pure gold.

Herve Berthoule/Photo Researchers

Types of Minerals

MAINIDEA Minerals are classified based on their chemical properties and characteristics.

Essential Questions

- What are the major mineral groups?
- How is the silicon-oxygen tetrahedron illustrated?
- How are minerals used?

Review Vocabulary

chemical bond: the force that holds two atoms together

New Vocabulary

silicate
tetrahedron
ore
gem

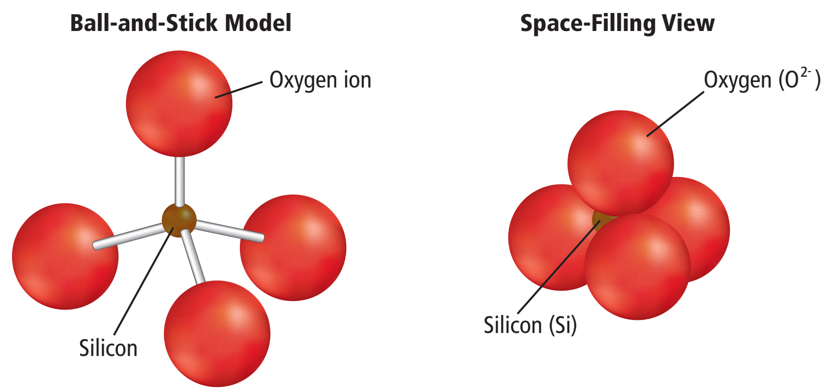
EARTH SCIENCE 4 YOU Everything on Earth is classified into various categories. Food, animals, and music are all classified according to certain properties or features. Minerals are no different; they, too, are classified into groups.

Mineral Groups

You have learned that elements combine in many different ways and proportions. One result is the thousands of different minerals present on Earth. In order to study these minerals and understand their properties, geologists have classified them into groups. Each group has a distinct chemical nature and specific characteristics.

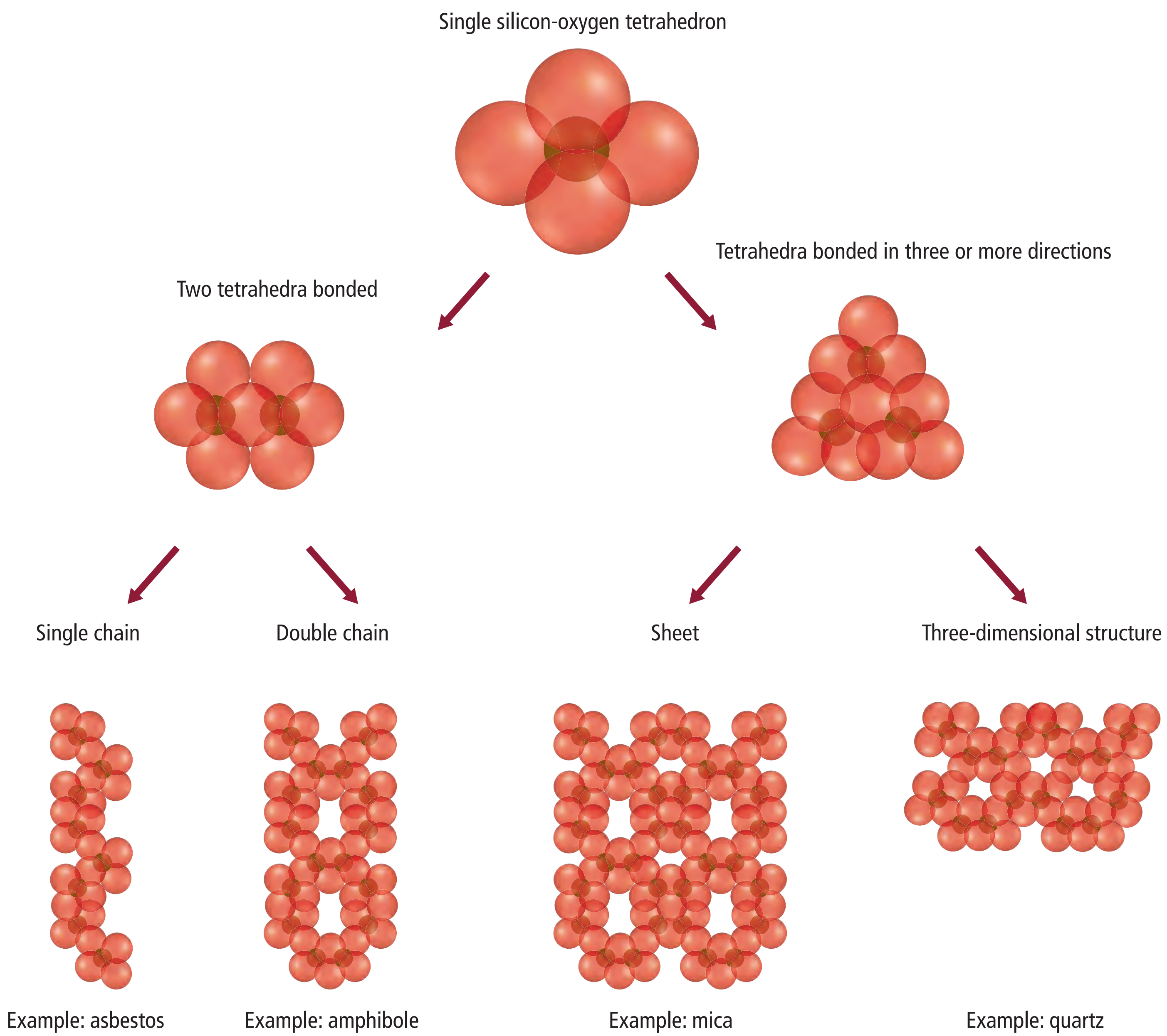
Silicates Oxygen is the most abundant element in Earth's crust, followed by silicon. Minerals that contain silicon and oxygen, and usually one or more additional elements, are known as **silicates.** Silicates make up approximately 96 percent of the minerals present in Earth's crust. The two most common minerals, feldspar and quartz, are silicates. The basic building block of the silicates is the silicon-oxygen tetrahedron, shown in **Figure 12.** A **tetrahedron** (plural, tetrahedra) is a geometric solid having four sides that are equilateral triangles, resembling a pyramid. Recall that the electrons in the outermost energy level of an atom are called valence electrons. The number of valence electrons determines the type and number of chemical bonds an atom will form. Because silicon atoms have four valence electrons, silicon has the ability to bond with four oxygen atoms. As shown in **Figure 13,** silicon-oxygen tetrahedra can share oxygen atoms. This structure allows tetrahedra to combine in a number of ways, which accounts for the large diversity of structures and properties of silicate minerals.

Figure 12 The silicate polyatomic ion SiO_4^{4-} forms a tetrahedron in which a central silicon atom is covalently bonded to oxygen atoms.
Specify *How many atoms are in one tetrahedron?*



VISUALIZING the Silicon-Oxygen Tetrahedron

Figure 13 A silicon-oxygen tetrahedron contains four oxygen atoms bonded to a central silicon atom. Chains, sheets, and complex structures form when tetrahedra share oxygen atoms. These structures and the types of metal ions bonded to them determine the numerous silicate minerals that are present on Earth.



Concepts In Motion View an **animation of bonding of the silicon-oxygen tetrahedron.**

■ **Figure 14** The differences in silicate minerals are due to the differences in the arrangement of their silicon-oxygen tetrahedra. Certain types of asbestos consist of weakly bonded double chains of tetrahedra, while mica consists of weakly bonded sheets of tetrahedra.

VOCABULARY

SCIENCE USAGE V. COMMON USAGE

Phyllo

Science usage: the sheets of silica tetrahedra

Common usage: sheets of dough used to make pastries and pies

Individual tetrahedron ions are strongly bonded. They can bond together to form sheets, chains, and complex three-dimensional structures. The bonds between the atoms help determine several mineral properties, including a mineral's cleavage or fracture. For example, mica, shown in **Figure 14,** is a sheet silicate, also called a phyllosilicate, where positive potassium or aluminum ions bond the negatively charged sheets of tetrahedra together. Mica separates easily into sheets because the attraction between the tetrahedra and the aluminum or potassium ions is weak. Asbestos, also shown in **Figure 14,** consists of double chains of tetrahedra that are weakly bonded together. This results in the fibrous nature shown in **Figure 14.**

Carbonates Oxygen combines easily with almost all other elements, and forms other mineral groups, such as carbonates. Carbonates are minerals composed of one or more metallic elements and the carbonate ion CO_3^{2-}. Examples of carbonates are calcite, dolomite, and rhodochrosite. Carbonates are the primary minerals found in rocks such as limestone and marble. Some carbonates have distinctive colorations, such as the colorful varieties of calcite and the pink of rhodochrosite shown in **Figure 16.**

■ **Figure 15**

Mineral Use Through Time

The value and uses of minerals have changed over time.

3300–3000 B.C. Bronze weapons and tools become common in the Near East as large cities and powerful empires arise.

800 B.C. Diamond use spreads from India to other parts of the world to be used for cutting, engraving, and in ceremonies.

12,000–9000 B.C. The demand for flint—a microcrystalline quartz used for tools—produces the first known long-distance trade route.

1200–1000 B.C. In the Near East, bronze becomes scarce and is replaced by iron in tools and weapons.

506 B.C. Rome takes over the salt industry at Ostia. The word *salary* comes from *salarium argentums,* the salt rations paid to Roman soldiers.

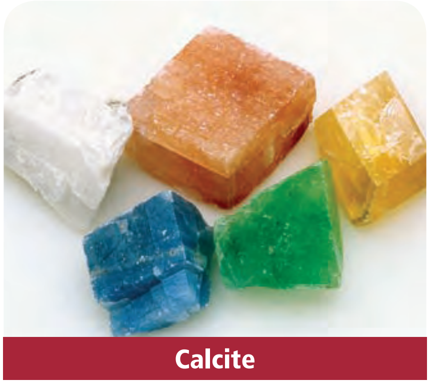


Figure 16 Carbonates such as calcite and rhodochrosite occur in distinct colors due to trace elements found in them.

Oxides Oxides are compounds of oxygen and a metal. Hematite (Fe_2O_3) and magnetite (Fe_3O_4) are common iron oxides and good sources of iron. The mineral uraninite (UO_2) is valuable because it is the major source of uranium, which is used to generate nuclear power.

Other Groups Other major mineral groups are sulfides, sulfates, halides, and native elements. Sulfides, such as pyrite (FeS_2), are compounds of sulfur and one or more elements. Sulfates, such as anhydrite ($CaSO_4$), are composed of elements and the sulfate ion SO_4^{2-}. Halides, such as halite (NaCl), are made up of chloride or fluoride along with calcium, sodium, or potassium. A native element such as silver (Ag) or copper (Cu), is made up of one element only.

Economic Minerals

Minerals are virtually everywhere. They are used to make computers, cars, televisions, desks, roads, buildings, jewelry, beds, paints, sports equipment, and medicines, in addition to many other things. You can learn about the uses of minerals throughout history by examining **Figure 15.**

A.D. 200–400 Iron farming tools and weapons allow people to migrate across Africa clearing and cultivating land for agricultural settlement and driving out hunter-gatherer societies.

A.D. 500

800–900 Chinese alchemists combine saltpeter with sulfur and carbon to make gunpowder, which is first used for fireworks and later used for weapons.

1500

1546 South American silver mines help establish Spain as a global trading power, supplying silver needed for coinage.

1927 The first quartz clock improves timekeeping accuracy. The properties of quartz make it instrumental to the development of radio, radar, and computers.

2000

2006 There are 242 uranium-fueled nuclear power plants in operation worldwide with a net capacity of 369.566 GW(e).

2010 Over 60 individual minerals, including quartz, bauxite, and halite, contribute to the modern computer.

Explore **major mineral groups with an interactive table.** Concepts In Motion

Table 4 Major Mineral Groups

Group	Examples	Economic Use
Silicates	mica (biotite) olivine (Mg_2SiO_4) quartz (SiO_2) vermiculite	furnace windows gem (as peridot) timepieces potting soil additive; swells when wet
Sulfides	pyrite (FeS_2) marcasite (FeS_2) galena (PbS) sphalerite (ZnS)	used to make sulfuric acid; often mistaken for gold (fool's gold) jewelry lead ore zinc ore
Oxides	hematite (Fe_2O_3) corundum (Al_2O_3) uraninite (UO_2) ilmenite ($FeTiO_3$) chromite ($FeCr_2O_4$)	iron ore; red pigment abrasive, gem (as in ruby or sapphire) uranium source titanium source; pigment; replaced lead in paint chromium source, plumbing fixtures, auto accessories
Sulfates	gypsum ($CaSO_4 \cdot 2H_2O$) anhydrite ($CaSO_4$)	plaster, drywall; slows drying in cement plaster; name indicates absence of water
Halides	halite (NaCl) fluorite (CaF_2) sylvite (KCl)	table salt, stock feed, weed killer, food preparation and preservative steel manufacturing, enameling cookware fertilizer
Carbonates	calcite ($CaCO_3$) dolomite ($CaMg(CO_3)_2$)	Portland cement, lime, chalk Portland cement, lime; source of calcium and magnesium in vitamin supplements
Native elements	gold (Au) copper (Cu) silver (Ag) sulfur (S) graphite (C)	monetary standard, jewelry coinage, electrical wiring, jewelry coinage, jewelry, photography sulfa drugs and chemicals; match heads; fireworks pencil lead, dry lubricant

Figure 17 Parts of this athlete's wheelchair are made of titanium. Its light weight and extreme strength makes it an ideal metal to use.

Ric Feld/AP Images

Ores Many of the items just mentioned are made from ores. A mineral is an **ore** if it contains a valuable substance that can be mined at a profit. Hematite, for instance, is an ore that contains the element iron. Consider your classroom. If any items are made of iron, their original source might have been the mineral hematite. If there are items in the room made of aluminum, their original source was the ore bauxite. A common use of the metal titanium, obtained from the mineral ilmenite, is shown in **Figure 17. Table 4** summarizes the mineral groups and their major uses.

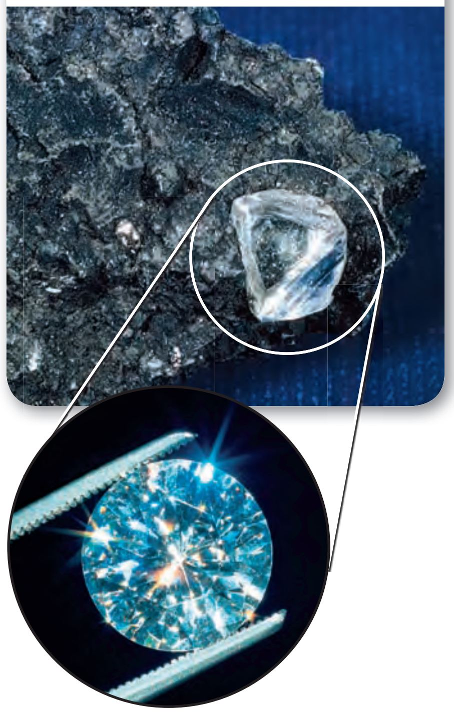
The classification of a mineral as an ore can also change if the supply of or demand for that mineral changes. Consider a mineral that is used to make computers. Engineers might develop a more efficient design or a less costly alternative material. In either of these cases, the mineral would no longer be used in computers. Demand for the mineral would drop. It would not be profitable to mine. The mineral would no longer be considered an ore.

Mines Ores that are located deep within Earth's crust are removed by underground mining. Ores that are near Earth's surface are obtained from large, open-pit mines. When a mine is excavated, unwanted rock and minerals, known as gangue, are dug up along with the valuable ore. The overburden must also be removed before the ore can be used. Removing the overburden can be expensive and, in some cases, harmful to the environment. If the cost of removing the overburden or separating the gangue becomes higher than the value of the ore itself, the mineral will no longer be classified as an ore. It would n o longer be economical to mine.

Gems What makes a ruby more valuable than mica? Rubies are rarer and more visually pleasing than mica. Rubies are thus considered gems. **Gems** are valuable minerals that are prized for their rarity and beauty. They are very hard and scratch resistant. Gems such as rubies, emeralds, and diamonds are cut, polished, and used for jewelry. Because of their rareness, rubies and emeralds are more valuable than diamonds. **Figure 18** shows a rough diamond and a polished diamond.

In some cases, the presence of trace elements can make one variety of a mineral more colorful and more prized than other varieties of the same mineral. Amethyst, for instance, is the gem form of quartz. Amethyst contains traces of iron, which gives the gem a purple color. The mineral corundum, which is often used as an abrasive, also occurs as rubies and sapphires. Red rubies contain trace amounts of chromium, while blue sapphires contain trace amounts of cobalt or titanium. Green emeralds are a variety of the mineral beryl, and are colored by trace amounts of chromium or vanadium.

Figure 18 The real beauty of gemstones is revealed once they are cut and polished.



Watch a **video about gems and minerals.**

Video

SECTION 2 REVIEW

Section Self-Check

Section Summary

- In silicates, one silicon atom bonds with four oxygen atoms to form a tetrahedron.
- Major mineral groups include silicates, carbonates, oxides, sulfides, sulfates, halides, and native elements.
- An ore contains a valuable substance that can be mined at a profit.
- Gems are valuable minerals that are prized for their rarity and beauty.

Understand Main Ideas

1. MAINIDEA **Formulate** a statement that explains the relationship between chemical elements and mineral properties.
2. **List** the two most abundant elements in Earth's crust. What mineral group do these elements form?
3. **Hypothesize** what some environmental consequences of mining ores might be.

Think Critically

4. **Hypothesize** why the mineral opal is often referred to as a mineraloid.
5. **Evaluate** which of the following metals is better to use in sporting equipment and medical implants: titanium—specific gravity = 4.5, contains only Ti; or steel—specific gravity = 7.7, contains Fe, O, Cr.

WRITING IN ▶ Earth Science

6. Design a flyer advertising the sale of a mineral of your choice. You might choose a gem or industrially important mineral. Include any information that you think will help your mineral sell.

(t)E. R. Degginger/Photo Researchers, (b)ImageState/Alamy Images eXpeditions!

ON SITE:

CRYSTALS AT LARGE IN MEXICO


Richard D. Fisher

Cave of Crystals, part of Naica Cave in Chihuahua, Mexico is known for its large crystals.

Eloy and Javier Delgado walk slowly into the Naica Cave in Chihuahua, Mexico. The cave is very hot, making it difficult for them to breathe. They enter a room in the cave and before them are huge 4.5-m crystals that are clear and brilliant. How did these crystals grow this large? What kinds of conditions make these crystals possible?

The climate inside the cave Large crystals of gypsum are present in the Cave of Crystals, a room in Naica Cave, located 300 m below Earth's surface. Temperatures in the cave hover around 58°C. The air here has a relative humidity of 90 to 100 percent. These extreme conditions mean that anyone entering the cave can remain only for a few minutes at a time.

Crystal formations in the cave The crystals in the Naica Cave are a crystalline form of gypsum called selenite. The crystals in this cave grow into three distinct shapes. Crystals that grow from the floor of the cave are plantlike in appearance. They are grayish in color from the mud that seeps into them as they grow. Swordlike crystals cover the walls of the cave. These crystals grow to lengths of 0.5 m to 1 m and are opaque white in color. Within the main room of the cave, there are crystals with masses of up to 50,000 kg and up to 11 m long and 1 m wide.

How did these crystals form? Crystals need several things in order to form. First, they need a space—in this case, a cave. Caves form as a result of water circulating along weak planes in a rock. Over time, the rock dissolves and a cave is formed. Second, crystals need a source of water that is rich in dissolved minerals. Crystal formation also depends on factors such as pressure, temperature, level of water in the cave, and the chemistry of the mineral-rich water.

Geologists have determined that the crystals' massive sizes resulted from the steady temperature of about 58°C while the cave was full of mineral-rich water. As long as the crystals remained in this environment, they continued to grow. In 1985, miners lowered the water table and unknowingly drained the cave, halting the growth of the crystals. Scientists hypothesize that the largest crystals are about 600,000 years old.

WRITING IN ▶ Earth Science

Illustrate Research the processes that form crystals in a cave. Choose a cave and design a brochure describing and illustrating the types of crystals found there.

WebQuest

(bkgd)fStop/Getty Images

GeoLAB

iLab Station

Design Your Own: Make a Field Guide for Minerals

Background: **Have you ever used a field guide to identify a bird, flower, rock, or insect? If so, you know that field guides include more than photographs. A typical field guide for minerals might include background information about minerals in general and specific information about the formation, properties, and uses of each mineral.**

Question: *Which mineral properties should be included in a field guide to help identify unknown minerals?*

Materials

Choose materials that would be appropriate for this lab.

mineral samples
magnifying lens
glass plate
streak plate
the Mohs scale of mineral hardness
steel file or nail
piece of copper
paper clip
magnet
dilute hydrochloric acid
dropper
Reference Handbook

Safety Precautions

Procedure

1. Read and complete the lab safety form.
2. As a group, list the steps that you will take to create your field guide. Keep the available materials in mind as you plan your procedure.
3. Should you test any of the properties more than once for any of the minerals? How will you determine whether certain properties indicate a specific mineral?
4. Design a data table to summarize your results. Be sure to include a column to record whether or not a particular test will be included in the guide. You can use this table as the basis for your field guide.
5. Read over your entire plan to make sure that all steps are in a logical order.
6. Have you included a step for additional research? You might have to use the library or the Internet to gather all the necessary information for your field guide
7. What additional information will be included in the field guide? Possible data include how each mineral formed, its uses, its chemical formula, and a labeled photograph or drawing of the mineral.
8. Make sure your teacher approves your plan before you proceed.

Analyze and Conclude

1. **Interpret** Which properties were most reliable for identifying minerals? Which properties were least reliable? Discuss reasons that one property is more useful than others.
2. **Observe and Infer** What mineral reacted with the hydrochloric acid? Why did the mineral bubble? Write the balanced equation that describes the chemical reaction that took place between the mineral and the acid.
3. **Summarize** What information did you include in the field guide? What resources did you use to gather your data? Describe the layout of your field guide.
4. **Evaluate** the advantages and disadvantages of field guides.
5. **Conclude** Based on your results, is there any one definitive test that can always be used to identify a mineral? Explain your answer.

WRITING IN ▶ Earth Science

Peer Review Trade field guides with another group and test them out by using them to identify a new mineral. Provide feedback to the authors of the guide that you use.

CHAPTER 4 STUDY GUIDE

BIGIDEA **Minerals are an integral part of daily life.**

Vocabulary Practice

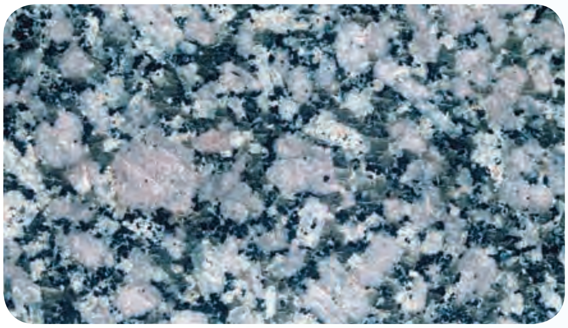
VOCABULARY

- mineral
- crystal
- luster
- hardness
- cleavage
- fracture
- streak
- specific gravity

SECTION 1 What is a mineral?

MAINIDEA **Minerals are naturally occurring, solid, inorganic compounds or elements.**

- A mineral is a naturally occurring, inorganic solid with a specific chemical composition and a definite crystalline structure.
- A crystal is a solid in which the atoms are arranged in repeating patterns.
- Minerals form from magma, supersaturated solutions, or from evaporation of solutions in which they are dissolved.
- Minerals can be identified based on physical and chemical properties.
- The most reliable way to identify a mineral is by using a combination of several tests.



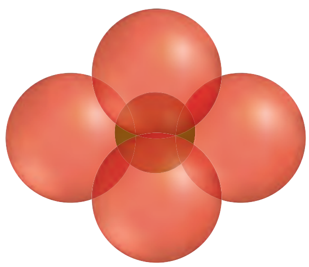
VOCABULARY

- silicate
- tetrahedron
- ore
- gem

SECTION 2 Types of Minerals

MAINIDEA **Minerals are classified based on their chemical properties and characteristics.**

- In silicates, one silicon atom bonds with four oxygen atoms to form a tetrahedron.
- Major mineral groups include silicates, carbonates, oxides, sulfides, sulfates, halides, and native elements.
- An ore contains a valuable substance that can be mined at a profit.
- Gems are valuable minerals that are prized for their rarity and beauty.



CHAPTER 4 ASSESSMENT

Chapter Self-Check

VOCABULARY REVIEW

Use what you know about the vocabulary terms listed on the Study Guide to answer the following questions.

1. What is a naturally occurring, solid, inorganic compound or element?
2. What term refers to the regular, geometric shapes that occur in many minerals?
3. What is the term for minerals containing silicon and oxygen?

Explain the relationship between the vocabulary terms in each pair.

4. ore, gem
5. silicate, tetrahedron

Complete the sentences below using vocabulary terms from the Study Guide.

6. Minerals that break randomly exhibit _________.
7. The _________ test determines what materials a mineral will scratch.

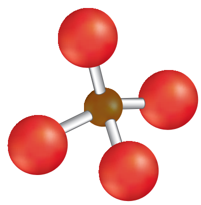
UNDERSTAND KEY CONCEPTS

Use the photo below to answer Question 8.

Matt Meadows

8. Which mineral property is being tested?
   A. texture **C.** cleavage
   B. hardness **D.** fluorescence
9. Which property causes the mineral galena to break into tiny cubes?
   A. density **C.** hardness
   B. crystal structure **D.** luster
10. What characteristic is used for classifying minerals into individual groups?
    A. internal atomic structure
    B. presence or absence of silica tetrahedrons
    C. chemical composition
    D. density and hardness
11. A mineral has a mass of 100 g and a volume of 50 cm^3. What is its density?
    A. 5000 g/cm^3
    B. 2 g/cm^3
    C. 5 g/cm^3
    D. 150 g/cm^3
12. What is the correct chemical formula for a silicon-oxygen tetrahedron?
    A. SiO_2
    B. $Si_2O_2^{+4}$
    C. SiO_4^{-4}
    D. Si_2O_2

Use the diagram below to answer Questions 13 and 14.



13. Where do the tetrahedra bond to each other?
    A. the center of the silicon atom
    B. at any oxygen atom
    C. only the top oxygen atom
    D. only the bottom oxygen atoms
14. What group of minerals is composed mainly of these tetrahedra?
    A. silicates **C.** carbonates
    B. oxides **D.** sulfates
15. Which is an example of a mineral whose streak cannot be determined with a porcelain streak plate?
    A. hematite
    B. gold
    C. feldspar
    D. magnetite

16. Which is one of the three most common elements in Earth's crust?
   A. sodium
   B. silicon
   C. iron
   D. carbon

Use the table below to answer Question 17.

Mineral Formulas	
Name	**Formula**
Quartz	SiO_2
Feldspar	$NaAlSi_3O_8$— $CaAl_2Si_2O_8$ & $KalSi_3O_8$
Amphibole	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$ $Fe_7Si_8O_{22}(OH)_2$
Olivine	$(Mg,Fe)_2SiO_4$

17. What is the main factor that determines the formation of the minerals listed in the table?
   A. rate of magma cooling
   B. temperature of the magma
   C. presence or absence of water
   D. changes in pressure

18. Calcite is the dominant mineral in the rock limestone. In which mineral group does it belong?
   A. silicates
   B. oxides
   C. carbonates
   D. sulfates

19. What mineral fizzes when it comes in contact with hydrochloric acid?
   A. quartz
   B. gypsum
   C. calcite
   D. fluorite

20. *Dull, silky, waxy, pearly,* and *earthy* are terms that best describe which property of minerals?
   A. luster
   B. color
   C. streak
   D. cleavage

21. For a mineral to be considered an ore, which requirement must it meet?
   A. It must be a common mineral.
   B. Its production must not generate pollution.
   C. It must be naturally occurring.
   D. Its production must generate a profit.

CONSTRUCTED RESPONSE

22. **Explain** why rubies and sapphires, which are both forms of the mineral corundum, are different colors.

23. **Describe** the visual effect of placing a piece of clear, Iceland spar on top of the word *geology* in a textbook.

24. **Summarize** the process of sugar crystals forming in a glass of sugar-sweetened hot tea.

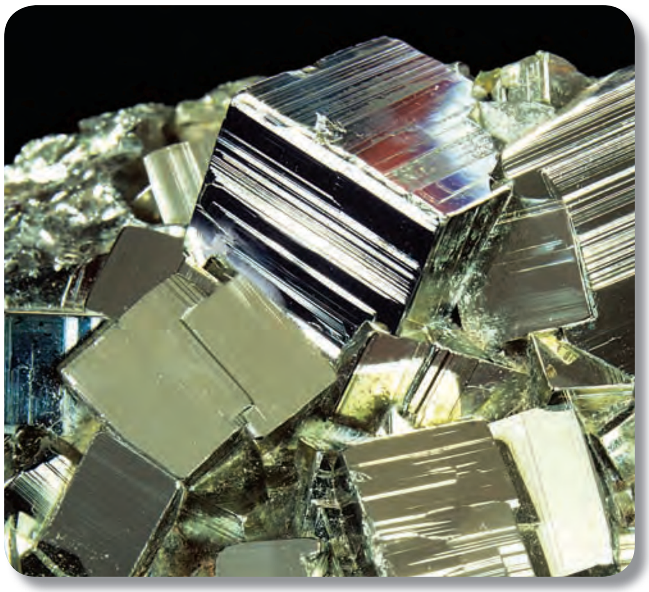
25. **Hypothesize** which mineral properties are the direct result of the arrangement of atoms or ions in a crystal. Explain your answer.

26. **Compare and Contrast** Diamond and graphite have the same chemical composition. Compare and contrast these two to explain why diamond is a gem and graphite is not.

THINK CRITICALLY

27. **Describe** the differences that might be exhibited by the garnets listed in **Table 1.**

Use the figure below to answer Question 28.



Martin Bond/Photo Researchers

28. **Illustrate** what the atomic structure might be if the crystal shape is an external reflection of it.

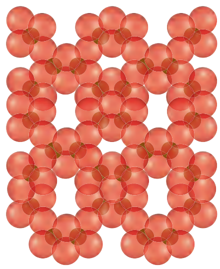
29. **Recommend** which minerals, other than diamond, would be best for making sandpaper. Explain your answer. Refer to **Table 2.**

30. **Decide** which of the following materials are not minerals, and explain why: petroleum, wood, coal, steel, concrete, and glass.

31. **Infer** how early prospectors used density to determine whether they had found gold or pyrite in a mine.

32. **Assess** Imagine that a new gem is discovered that is more beautiful than the most stunning diamond or ruby. Assess the factors that will determine its cost compared to other known gems.

Use the figure below to answer Questions 33–34.



33. **Infer** Mica is a mineral with a sheet silicate structure. The atomic arrangement is shown above. Infer what is holding these sheets, which consist of negatively charged silicon-oxygen tetrahedra, together.

34. **Describe** the type of cleavage that occurs in minerals with the atomic arrangement shown.

CONCEPT MAPPING

35. Create a concept map using the following terms: *silicates, oxides, halides, sulfates, sulfides, native elements,* and *carbonates.* Add any other terms that are helpful. For more help, refer to the *Skillbuilder Handbook.*

CHALLENGE QUESTION

36. **Arrange** In addition to sheet silicates, there are chain silicates, tectosilicates, and cyclosilicates. Arrange six silicon-oxygen tetrahedra in a cyclosilicate form. Be sure to bond the oxygen atoms correctly.

WRITING IN Earth Science

37. Imagine that you are planning a camping trip. What tools should you pack if you want to identify interesting minerals? How would you use these tools?

DBQ Document–Based Questions

Data obtained from: Plunkert, P.A. 2005. Mineral resource of the month: Aluminum. *Geotimes* 50:57.

Aluminum is an abundant metallic element in Earth's crust. It is lightweight, ductile [bendable], corrosion resistant, and a good conductor of electricity. It is used most often in the manufacture of cars, buses, trailers, ships, aircraft, railway and subway cars. Other uses include beverage cans, aluminum foil, machinery, and electrical equipment.

Aluminum is produced from bauxite (hydrated aluminum-oxide) deposits, located mostly in Guinea, Australia, and South America. The United States does not have bauxite deposits; it imports it from Brazil, Guinea, and Jamaica. Total world aluminum production is approximately 30 million metric tons per year. U.S. aluminum production is less than U.S. aluminum consumption. Leading aluminum producers are China and Russia. A major part (3 million metric tons per year) of the U.S. aluminum supply comes from recycling.

38. Interpret the relationship between aluminum's resistance to corrosion and its use in transportation vehicles.

39. Propose a plan for how the United States can increase aluminum production without increasing the amount it imports.

40. Predict the possible effects an increase in U.S. production would have on Guinea, Jamaica, and China.

CUMULATIVE REVIEW

41. How do different isotopes of an element differ from each other? **(Chapter 3)**

42. Why is an understanding of the study of Earth science important to us as residents of Earth? **(Chapter 1)**

MULTIPLE CHOICE

1. What is the second most abundant element in Earth's crust?
   A. nitrogen
   B. oxygen
   C. silicon
   D. carbon

Use the table below to answer Questions 2 and 3.

Mineral Characteristics			
Mineral	**Hardness**	**Specific Gravity**	**Luster/Color**
Feldspar	6–6.5	2.5–2.8	nonmetallic/colorless or white
Fluorite	4	3–3.3	nonmetallic/yellow, blue, purple, rose, green, or brown
Galena	2.5–2.75	7.4–7.6	metallic/grayish black
Quartz	7	2.65	nonmetallic/colorless in pure form

2. What is the hardest mineral in the table?
   A. feldspar
   B. fluorite
   C. galena
   D. quartz

3. Which mineral has a metallic luster?
   A. feldspar
   B. fluorite
   C. galena
   D. quartz

4. What can be inferred about an isotope that releases radiation?
   A. It has unstable nuclei.
   B. It has stable nuclei.
   C. It has the same mass number as another element.
   D. It is not undergoing decay.

5. How do electrons typically fill energy levels?
   A. from lowest to highest
   B. from highest to lowest
   C. in no predictable pattern
   D. all in one energy level

6. Which is the most reliable clue to a mineral's identity?
   A. color
   B. streak
   C. hardness
   D. luster

Use the table below to answer Questions 7 and 8.

Mineral	Hardness
Talc	1
Gypsum	2
Calcite	3
Fluorite	4
Apatite	5
Feldspar	6
Quartz	7
Topaz	8
Corundum	9
Diamond	10

7. Which mineral will scratch feldspar but not topaz?
   A. quartz
   B. calcite
   C. apatite
   D. diamond

8. What can be implied about diamond based on the table?
   A. It is the heaviest mineral.
   B. It is the slowest mineral to form.
   C. It has the most defined crystalline structure.
   D. It cannot be scratched by any other mineral.

9. A well-planned experiment must have all of the following EXCEPT
   A. technology
   B. a control
   C. a hypothesis
   D. collectible data

10. What name is given to the imaginary line circling Earth halfway between the north and south poles?
    A. prime meridian
    B. equator
    C. latitude
    D. longitude

SHORT ANSWER

Use the conversion factor and table below to answer Questions 11–13.

1.0 carat = 0.2 grams

Diamond	Carats	Grams
Uncle Sam: largest diamond found in United States	40.4	?
Punch Jones: second largest; named after boy who discovered it	?	6.89
Theresa: discovered in Wisconsin in 1888	21.5	4.3
2001 diamond production from western Australia	21,679,930	?

11. List the three diamonds from least to greatest according to carats, and list the carats.

12. How many kilograms of diamonds were produced in western Australia in 2001?

13. Why would a diamond excavator want to convert the diamond measurement from carats to grams?

14. Why are map scales important parts of a map?

15. Discuss how a scientist might use a Landsat satellite image to determine the amount of pollution being produced by a city.

16. Why might a mineral no longer be classified as an ore?

READING FOR COMPREHENSION

Silicon Valley

Silicon (Si) is the second most abundant element in Earth's crust, but we didn't hear much about it until Silicon Valley. It is present in measurable amounts in nearly every rock, in all natural waters, as dust in the air, in the skeletons of many plants and some animals, and even in the stars. Silicon is never found in the free state like gold or silver, but is always with oxygen (O), aluminum (Al), magnesium (Mg), calcium (Ca), sodium (Na), potassium (K), iron (Fe), or other elements in combinations called the silicates. Silicates are the largest and most complicated group of minerals. Silicon is dull gray in appearance and has a specific gravity of 2.42. It has valence electrons like carbon (C) and can form a vast array of chemical compounds like silicon carbide abrasive, silicon rubber and caulking, oils and paints. Pure silicon is used in semiconductors, as solar panels to generate electricity from light, and in microchips for transistors.

Information obtained from: Ellison, B. Si and SiO_2...or what a difference a little O makes. (online resource accessed October 2006.)

17. According to the text, what is the most challenging aspect of silicon?
    A. It has valence electrons.
    B. It is dull gray in appearance.
    C. It is never found in its free state.
    D. It is present in many places.

18. Which is NOT a use of silicon as a chemical compound given in this passage?
    A. silicon rubber and caulking
    B. silicon carbide abrasive
    C. microchips for transistors
    D. oils and paints

19. Why can it be said that the occurrence of silicon is universal?

NEED EXTRA HELP?																
If You Missed Question . . .	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Review Section . . .	4.2	4.1	4.1	3.1	3.6	4.1	4.1	4.1	1.2	2.1	4.2	4.2	1.2	2.2	2.3	3.2

CHAPTER 5

Igneous Rocks

BIGIDEA **Igneous rocks were the first rocks to form as Earth cooled from a molten mass to the crystalline rocks of the early crust.**

SECTIONS

1 What are igneous rocks?

2 Classification of Igneous Rocks

LaunchLAB

iLab Station

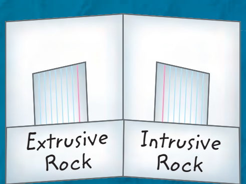
How are minerals identified?

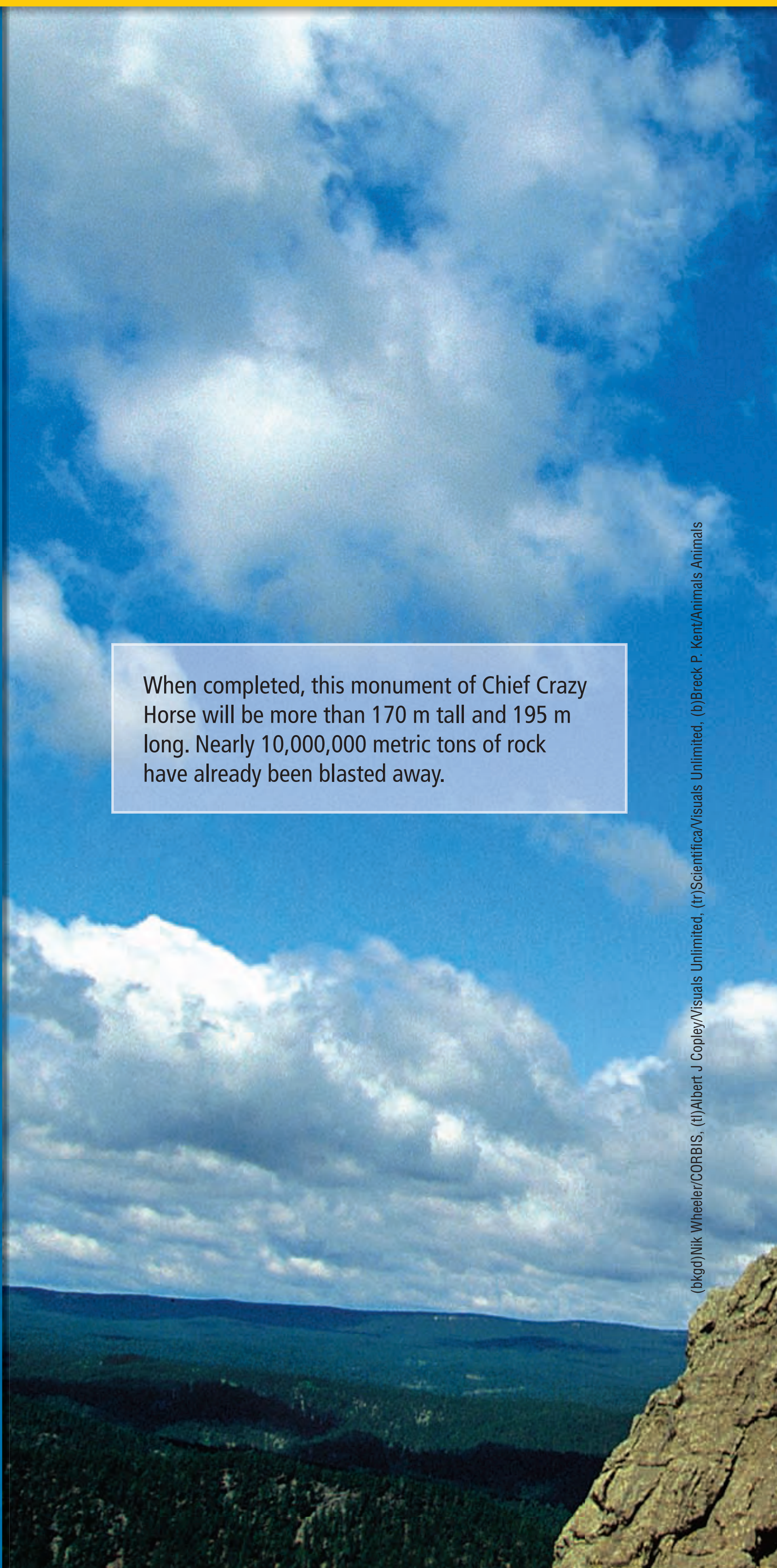
Igneous rocks are composed of different types of minerals. In this lab, you will learn that it is often possible to identify the different minerals in a sample of rock.

FOLDABLES® Study Organizer

Types of Igneous Rocks

Make a pocket book using the labels shown. Use it to organize your notes on the types of igneous rocks and how they form.





When completed, this monument of Chief Crazy Horse will be more than 170 m tall and 195 m long. Nearly 10,000,000 metric tons of rock have already been blasted away.

(bkgd)Nik Wheeler/CORBIS, (tr)Albert J Copley/Visuals Unlimited, (tr)Scientifica/Visuals Unlimited, (b)Breck P. Kent/Animals Animals


Go online!
connectED.mcgraw-hill.com
Feldspar
Biotite
Quartz

SECTION 1

What are igneous rocks?

MAINIDEA Igneous rocks are the rocks that form when molten material cools and crystallizes.

Essential Questions

- How do igneous rocks form?
- How can the composition of magma be described?
- What are the factors that affect how rocks melt and crystallize?

Review Vocabulary

silicate: mineral that contains silicon and oxygen, and usually one or more other elements

New Vocabulary

lava
igneous rock
partial melting
Bowen's reaction series
fractional crystallization

EARTH SCIENCE 4 YOU At any given point in time, igneous rocks are forming somewhere on Earth. The location and the conditions that are present determine the types of igneous rocks that form.

Igneous Rock Formation

If you live near an active volcano, you can literally watch igneous rocks form. A hot, molten mass of rock can solidify into solid rock overnight. As you have learned, magma is molten rock below Earth's surface. **Lava** is magma that flows out onto Earth's surface. **Igneous rocks** form when lava or magma cools and crystallizes.

In the laboratory, most rocks must be heated to temperatures of 800°C to 1200°C before they melt. In nature, these temperatures are present in the upper mantle and lower crust. Where does this heat come from? Scientists theorize that the remaining energy from Earth's molten formation and the heat generated from the decay of radioactive elements are the sources of Earth's thermal energy.

Composition of magma The type of igneous rock that forms depends on the composition of the magma. Magma is often a slushy mix of molten rock, dissolved gases, and mineral crystals. The common elements present in magma are the same major elements that are in Earth's crust: oxygen (O), silicon (Si), aluminum (Al), iron (Fe), magnesium (Mg), calcium (Ca), potassium (K), and sodium (Na). Of all the compounds present in magma, silica is the most abundant and has the greatest effect on magma characteristics. As summarized in **Table 1,** magma is classified as basaltic, andesitic, or rhyolitic, based on the amount of silica it contains. Silica content affects melting temperature and impacts a magma's viscosity, or resistance to flow. Rhyolitic magma has a higher viscosity than basaltic magma.

Explore **magma composition with an interactive table.** Concepts In Motion

Table 1 Types of Magma

Group	Silica Content	Example Location
Basaltic	45–52%	Hawaiian Islands
Andesitic	52–66%	Cascade Mountains, Andes Mountains
Rhyolitic	more than 66%	Yellowstone National Park

Once magma is free of the overlying pressure of the rock layers around it, dissolved gases are able to escape into the atmosphere. Thus, the chemical composition of lava is slightly different from the chemical composition of the magma from which it developed.

Magma formation Magma can be formed either by melting of Earth's crust or by melting within the mantle. The four main factors involved in the formation of magma are temperature, pressure, water content, and the mineral content of the crust or mantle. Temperature generally increases with depth in Earth's crust. This temperature increase, known as the geothermal gradient, is plotted in **Figure 1.** Oil-well drillers and miners have firsthand experience with the geothermal gradient. Drill bits, such as the one shown in **Figure 2,** can encounter temperatures in excess of 200°C when drilling deep oil wells.

Pressure also increases with depth. This is a result of the weight of overlying rock. Laboratory experiments show that as pressure on a rock increases, its melting point also increases. Thus, a rock that melts at 1100°C at Earth's surface will melt at 1400°C at a depth of 100 km.

The third factor that affects the formation of magma is water content. Rocks and minerals often contain small percentages of water, which changes the melting point of the rocks. As water content increases, the melting point decreases.

READING CHECK **List** the main factors involved in magma formation.

Mineral content In order to better understand how the types of elements and compounds present give magma its overall character, it is helpful to discuss this fourth factor in more detail. Different minerals have different melting points. For example, rocks such as basalt, which are formed of olivine, calcium feldspar, and pyroxene (pi RAHK seen), melt at higher temperatures than rocks such as granite, which contain quartz and potassium feldspar. Granite has a melting point that is lower than basalt's melting point because granite contains more water and minerals that melt at lower temperatures. In general, rocks that are rich in iron and magnesium melt at higher temperatures than rocks that contain higher levels of silicon.

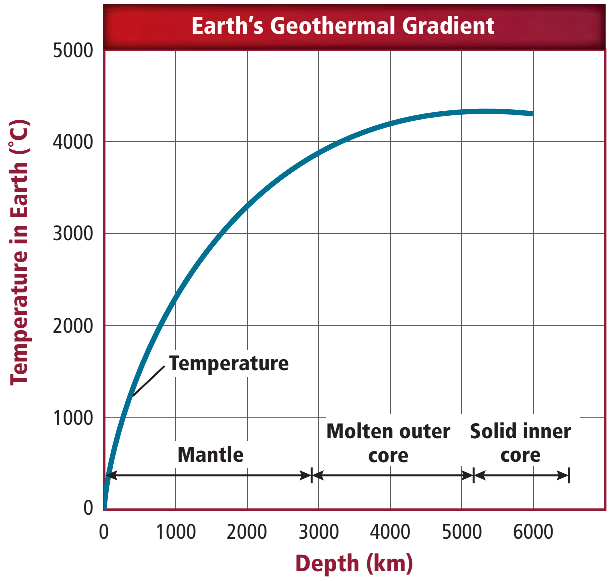


Figure 1 The average geothermal gradient in the crust is about 25°C/km, but scientists think that it drops sharply in the mantle to as low as 1°C/km.

Figure 2 The temperature of Earth's upper crust increases with depth by about 30°C for each 1 km. At a depth of 3 km, this drill bit will encounter rock that is close to the temperature of boiling water.

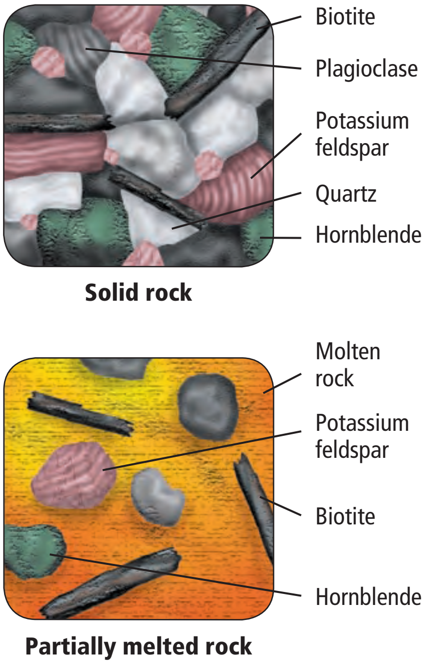


Figure 3 As the temperature increases in an area, minerals begin to melt.
Determine *What can you suggest about the melting temperature of quartz based on this diagram?*

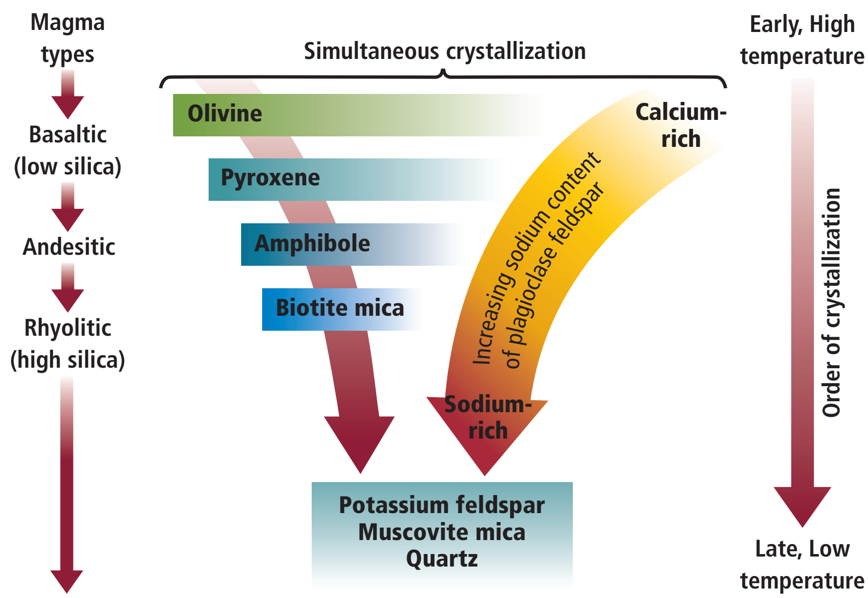
Partial melting Suppose you froze melted candle wax and water in an ice cube tray. If you took the tray out of the freezer and left it at room temperature, the ice would melt, but the candle wax would not. This is because the two substances have different melting points. Rocks melt in a similar way because the minerals they contain have different melting points. Not all parts of a rock melt at the same temperature. This explains why magma is often a slushy mix of crystals and molten rock. The process whereby some minerals melt at relatively low temperatures while other minerals remain solid is called **partial melting.** Partial melting is illustrated in **Figure 3.** As each group of minerals melts, different elements are added to the magma mixture thereby changing its composition. If temperatures are not high enough to melt the entire rock, the resulting magma will have a different composition than that of the original rock. This is one way in which different types of igneous rocks form.

READING CHECK **Summarize** the formation of magma that has a different chemical composition from the original rock.

Bowen's Reaction Series

In the early 1900s, Canadian geologist N. L. Bowen demonstrated that as magma cools and crystallizes, minerals form in predictable patterns in a process now known as the **Bowen's reaction series. Figure 4** illustrates the relationship between cooling magma and the formation of minerals that make up igneous rock. Bowen discovered two main patterns, or branches, of crystallization. The right-hand branch is characterized by a continuous, gradual change of mineral compositions in the feldspar group. An abrupt change of mineral type in the iron-magnesium groups characterizes the left-hand branch.

Figure 4 On the left side of Bowen's reaction series, minerals rich in iron and magnesium change abruptly as the temperature of the magma decreases.
Compare *How does this compare to the feldspars on the right side of the diagram?*



Iron-rich minerals The left branch of Bowen's reaction series represents the iron-rich minerals. These minerals undergo abrupt changes as magma cools and crystallizes. For example, olivine is the first mineral to crystallize when magma that is rich in iron and magnesium begins to cool. When the temperature decreases enough for a completely new mineral, pyroxene, to form, the olivine that previously formed reacts with the magma and is converted to pyroxene. As the temperature decreases further, similar reactions produce the minerals amphibole and biotite mica.

Feldspars In Bowen's reaction series, the right branch represents the plagioclase feldspars, which undergo a continuous change of composition. As magma cools, the first feldspars to form are rich in calcium. As cooling continues, these feldspars react with magma, and their calcium-rich compositions change to sodium-rich compositions. In some instances, such as when magma cools rapidly, the calcium-rich crystals are unable to react completely with the magma. The result, as shown in **Figure 5**, is a zoned crystal with a calcium-rich core and sodium-rich outer layers.

■ **Figure 5** When magma cools quickly, a feldspar crystal might not have time to react completely with the magma and might retain a calcium-rich core. The result is a crystal with distinct calcium-rich and sodium-rich zones.

Fractional Crystallization

When magma cools, it crystallizes in the reverse order of partial melting. That is, the first minerals that crystallize from magma are the last minerals that melt. This process, called **fractional crystallization,** is similar to partial melting in that the composition of magma can change. In this case, however, early formed crystals are removed from the magma and cannot react with it. As minerals form and their elements are removed from the remaining magma, it becomes concentrated in silica as shown in **Figure 4.**

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MiniLAB

iLab Station

Compare Igneous Rocks

How do igneous rocks differ? Igneous rocks have many different characteristics. Color and crystal size are some of the features that differentiate igneous rocks.

Procedure

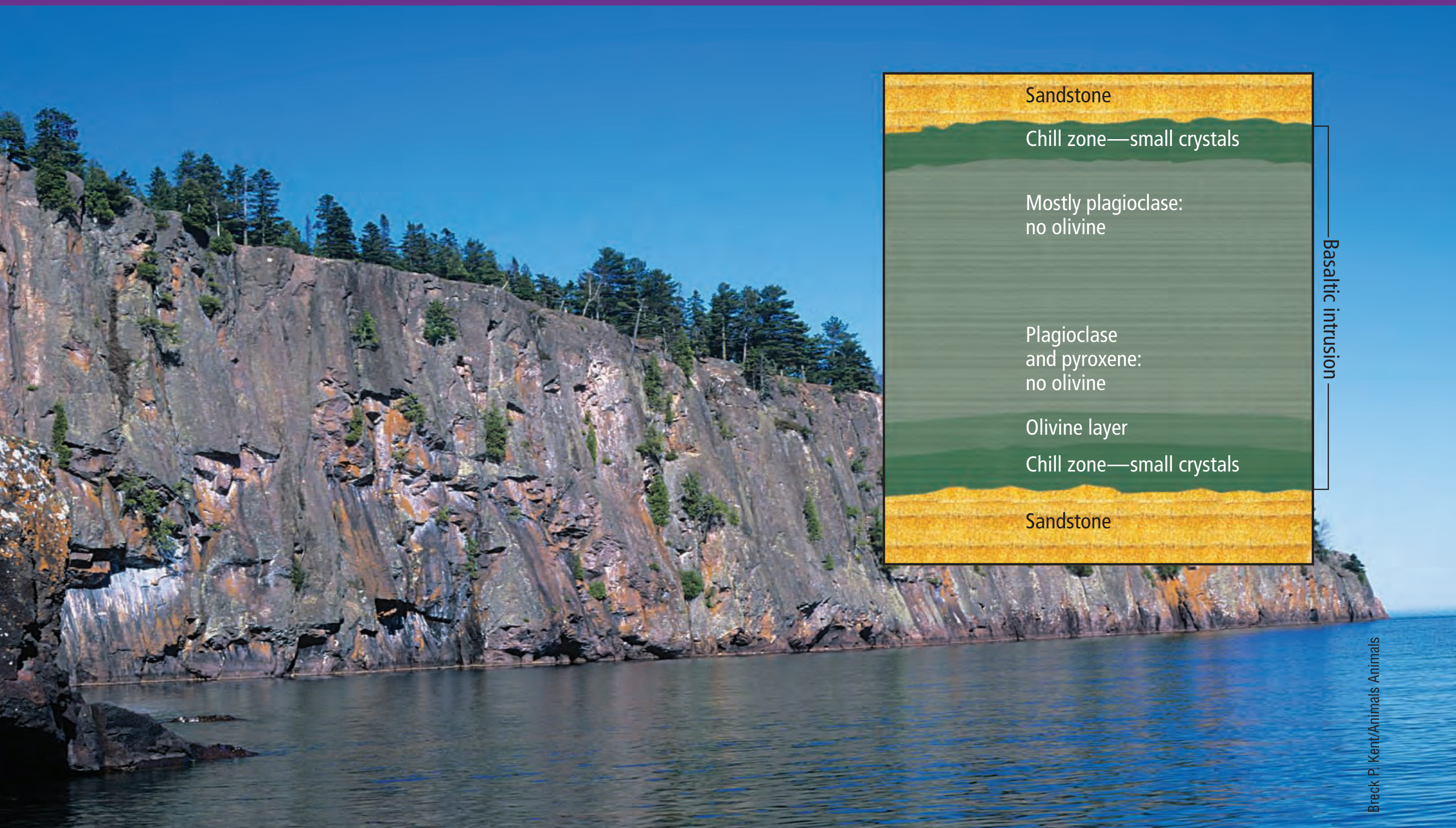
1. Read and complete the lab safety form.
2. Obtain a set of **igneous rock samples** from your teacher.
3. Carefully observe the following characteristics of each rock: overall color, crystal size, and, if possible, mineral composition.
4. Design a **data table** to record your observations.

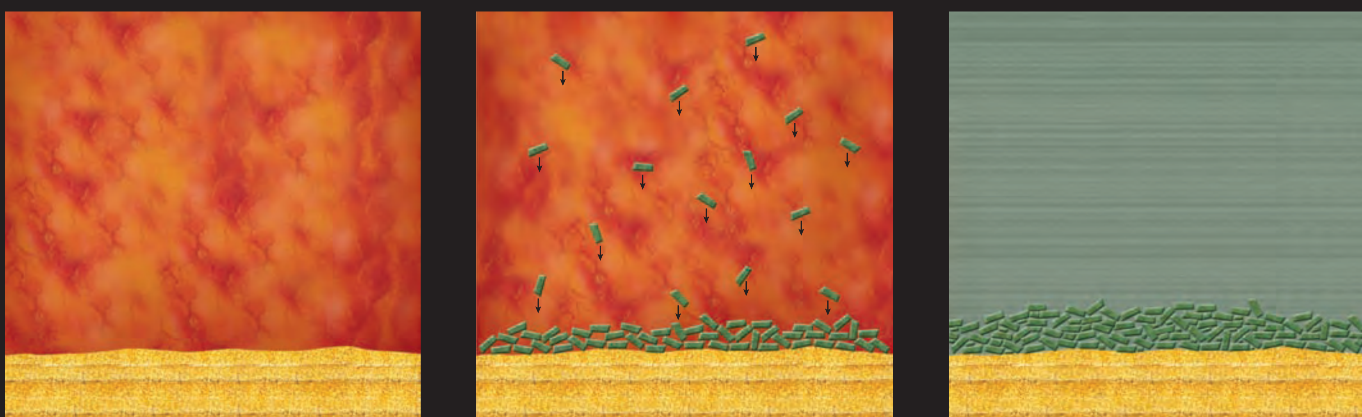
Analysis

1. **Classify** your samples as forming from either basaltic, andesitic, or rhyolitic magma. [Hint: The more silica in the rock, the lighter it is in color.]
2. **Compare and contrast** your samples using the data from the data table. How do they differ? What characteristics do each of the groups share?
3. **Speculate** in which order the samples crystallized. [Hint: Use Bowen's reaction series as a guide.]

VISUALIZING Fractional Crystallization and Crystal Settling

Figure 6 The Palisades Sill in the Hudson River valley of New York and New Jersey is a classic example of fractional crystallization and crystal settling. In this basaltic intrusion, small crystals formed in the chill zone as the outer areas of the intrusion cooled more quickly than the interior.





As magma in an intrusion begins to cool, crystals form and settle to the bottom. This layering of crystals is fractional crystallization.

View an **animation of the Palisades Sill.** Concepts In Motion

As is often the case with scientific inquiry, the discovery of Bowen's reaction series led to more questions. For example, if olivine converts to pyroxene during cooling, why is olivine present in some rocks? Geologists hypothesize that, under certain conditions, newly formed crystals are separated from the cooling magma, and the chemical reactions between the magma and the minerals stop. This can occur when crystals settle to the bottom of the magma body, and when liquid magma is squeezed from the crystal mush. This results in the formation of two distinct igneous bodies with different compositions. **Figure 6** illustrates this process and the concept of fractional crystallization with an example from the Hudson River valley in New York and New Jersey. This is one way in which the magmas listed in **Table 1** are formed.

As fractional crystallization continues, and more and more crystals are separated from the magma, the magma becomes more concentrated in silica, aluminum, and potassium. For this reason, the last two minerals to crystallize out of a cooling body of magma are potassium feldspar and quartz. Potassium feldspar is one of the most common feldspars in Earth's crust. Quartz often occurs in veins, as shown in **Figure 7,** because it crystallizes while the last liquid portion of magma is squeezed into rock fractures.

■ **Figure 7** These quartz veins represent the last remnants of a magma body that cooled and crystallized.

SECTION 1 REVIEW

Section Self-Check

Section Summary

- Magma consists of molten rock, dissolved gases, and mineral crystals.
- Magma is classified as basaltic, andesitic, or rhyolitic, based on the amount of silica it contains.
- Different minerals melt and crystallize at different temperatures.
- Bowen's reaction series defines the order in which minerals crystallize from magma.

Understand Main Ideas

1. MAINIDEA **Predict** the appearance of an igneous rock that formed as magma cooled quickly and then more slowly.
2. **List** the eight major elements present in most magmas. Include the chemical symbol of each element.
3. **Summarize** the factors that affect the formation of magma.
4. **Compare and contrast** magma and lava.

Think Critically

5. **Predict** If the temperature increases toward the center of Earth, why is the inner core solid?
6. **Infer** the silica content of magma derived from partial melting of an igneous rock. Would it be higher, lower, or about the same as the rock itself? Explain.

WRITING IN ▶ Earth Science

7. A local rock collector claims that she has found the first example of pyroxene and sodium-rich feldspar in the same rock. Write a commentary about her claim for publication in a rock collector society newsletter.

SECTION 2

Classification of Igneous Rocks

MAINIDEA **Classification of igneous rocks is based on mineral composition and texture.**

Essential Questions

- What are the different types and textures of igneous rocks?
- How do the cooling rates affect the grain sizes in igneous rocks?
- What are some of the uses of igneous rocks?

Review Vocabulary

fractional crystallization: a sequential process during which early formed crystals are removed from the melt and do not react with the remaining magma.

New Vocabulary

intrusive rock
extrusive rock
basaltic rock
granitic rock
texture
porphyritic texture
vesicular texture
pegmatite
kimberlite

EARTH SCIENCE 4 YOU **Many statues, floors, buildings, and countertops have something in common. Many of them are made of the popular rock type granite—one of the most abundant rocks in Earth's crust.**

Mineral Composition of Igneous Rocks

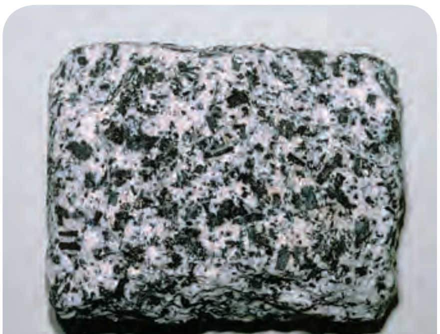
Igneous rocks are broadly classified as intrusive or extrusive. When magma cools and crystallizes below Earth's surface, **intrusive rocks** form. If the magma is injected into the surrounding rock, it is called an igneous intrusion. Crystals of intrusive rocks are generally large enough to see without magnification. Magma that cools and crystallizes on Earth's surface forms **extrusive rocks.** These are sometimes referred to as lava flows or flood basalts. The crystals that form in these rocks are small and difficult to see without magnification. Geologists classify igneous rocks by their mineral compositions. In addition, physical properties such as grain size and texture serve as clues for the identification of various igneous rocks.

Igneous rocks are classified according to their mineral compositions. **Basaltic rocks,** also called mafic rocks, are dark-colored, have lower silica contents, and contain mostly plagioclase and pyroxene. **Granitic rocks,** or felsic rocks, are light-colored, have high silica contents, and contain mostly quartz and feldspar. Rocks that have a composition of minerals that is somewhere in between basaltic and granitic are called intermediate rocks. They consist mostly of plagioclase feldspar and hornblende. **Figure 8** shows examples from these three main compositional groups of igneous rocks: gabbro is basaltic, granite is granitic, and diorite is intermediate. A fourth category called ultrabasic, or ultramafic, contains rocks with only iron-rich minerals such as olivine and pyroxene and are always dark. **Figure 9** summarizes igneous rock identification.

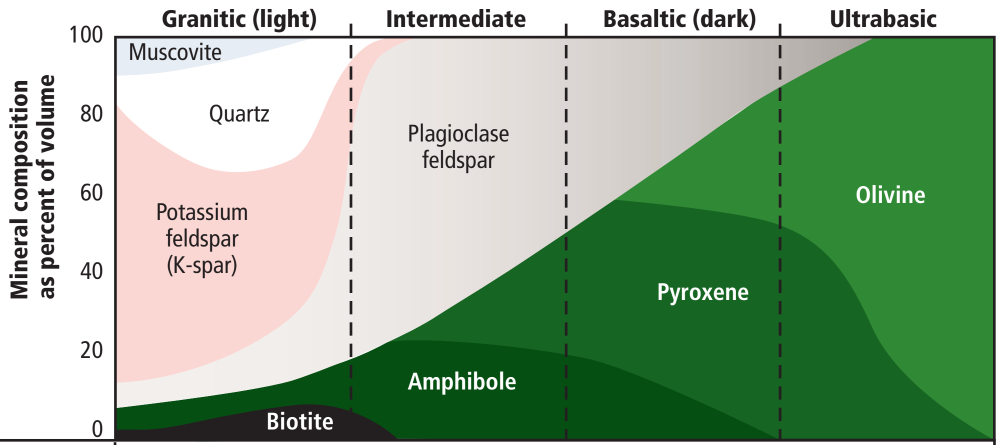
Figure 8 Differences in magma composition can be observed in the rocks that form when the magma cools and crystallizes.
Observe *Describe the differences you see in these rocks.*


Gabbro


Granite


Diorite

Igneous Rock Identification



Origin	Texture	Rock Names			
Intrusive	coarse-grained	granite	diorite	gabbro	peridotite
	porphyritic	porphyritic rhyolite or granite	porphyritic andesite or diorite	porphyritic basalt or gabbro	
Extrusive	fine-grained	rhyolite	andesite	basalt	
	glassy	obsidian			
	vesicular	pumice		scoria (vesicular basalt)	

■ **Figure 9** Rock type can be determined by estimating the relative percentages of minerals in the rocks.

Texture

In addition to differences in their mineral compositions, igneous rocks differ in the sizes of their grains or crystals. **Texture** refers to the size, shape, and distribution of the crystals or grains that make up a rock. For example, as shown in **Figure 10,** the texture of rhyolite can be described as fine-grained, while granite can be described as coarse-grained. The difference in crystal size can be explained by the fact that one rock is extrusive and the other is intrusive.

■ **Figure 10** Rhyolite, granite, and obsidian have different textures because they formed in different ways. Obsidian's glassy texture is a result of rapid cooling.

Figure 11 Rock textures provide information about a rock's formation. Evidence of the rate of cooling and the presence or absence of dissolved gases is preserved in the rocks shown here.

Crystal size and cooling rates When lava flows on Earth's surface, it cools quickly and there is not enough time for large crystals to form. The resulting extrusive igneous rocks, such as rhyolite, which is shown in **Figure 10,** have crystals so small that they are difficult to see without magnification. Sometimes, cooling occurs so quickly that crystals do not form at all. The result is volcanic glass, called obsidian, also shown in **Figure 10.** In contrast, when magma cools slowly beneath Earth's surface, there is sufficient time for large crystals to form. Thus, intrusive igneous rocks, such as granite, diorite, and gabbro, can have crystals larger than 1 cm.

Porphyritic rocks Look at the textures of the rocks shown in **Figure 11.** The top photo shows a rock with two different crystal sizes. This rock has a **porphyritic** (por fuh RIH tihk) **texture,** which is characterized by large, well-formed crystals surrounded by finer-grained crystals of the same mineral or different minerals.

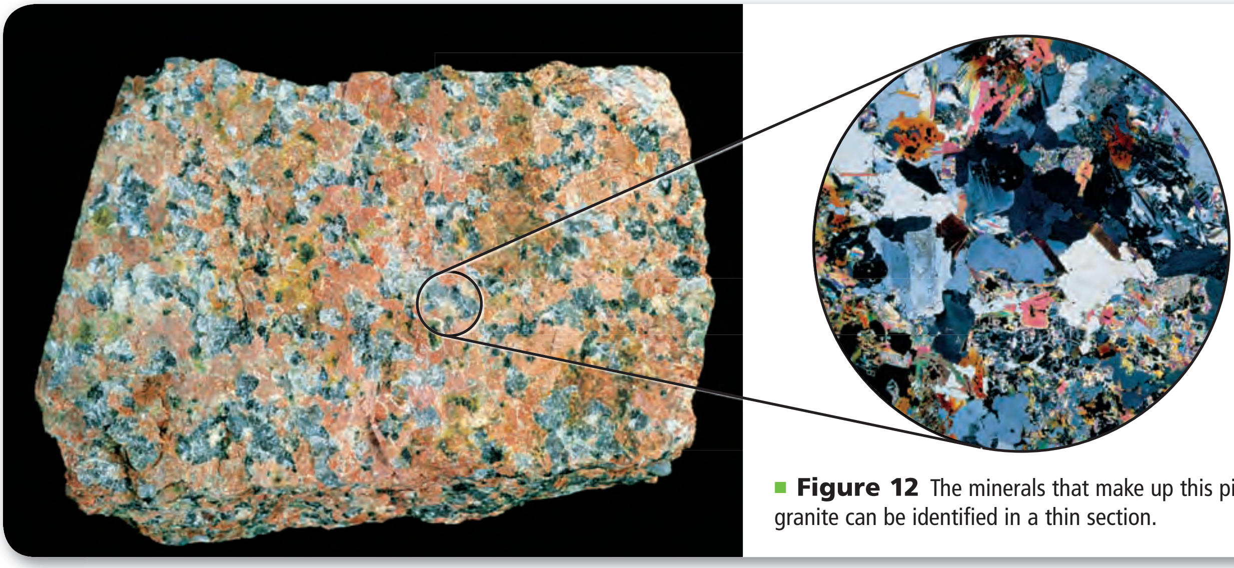
What causes minerals to form both large and small crystals in the same rock? Porphyritic textures indicate a complex cooling history during which a slowly cooling magma suddenly began cooling rapidly. Imagine a magma body cooling slowly, deep in Earth's crust. As it cools, the first crystals to form grow large. If this magma were to be suddenly moved higher in the crust, or if it erupted onto Earth's surface, the remaining magma would cool quickly and form smaller crystals.

Vesicular rocks Magma contains dissolved gases that escape when the pressure on the magma lessens. If the lava is thick enough to prevent the gas bubbles from escaping, holes called vesicles are left behind. The rock that forms looks spongy. This spongy appearance is called **vesicular texture.** Pumice and vesicular basalt are examples shown in **Figure 11.**

☑ READING CHECK **Explain** what causes holes to form in igneous rocks.

Thin Sections

It is usually easier to observe the sizes of mineral grains than it is to identify the mineral. To identify minerals, geologists examine samples that are called thin sections. A thin section is a slice of rock, generally 2 cm × 4 cm and only 0.03 mm thick. Because it is so thin, light is able to pass through it.



■ **Figure 12** The minerals that make up this piece of granite can be identified in a thin section.

When viewed through a special microscope, called a petrographic microscope, mineral grains exhibit distinct properties. These properties allow geologists to identify the minerals present in the rock. For example, feldspar grains often show a distinct banding called twinning. Quartz grains might appear wavy as the microscope stage is rotated. Calcite crystals become dark, or extinguish, as the stage is rotated. **Figure 12** shows the appearance of a thin section of granite under a petrographic microscope.

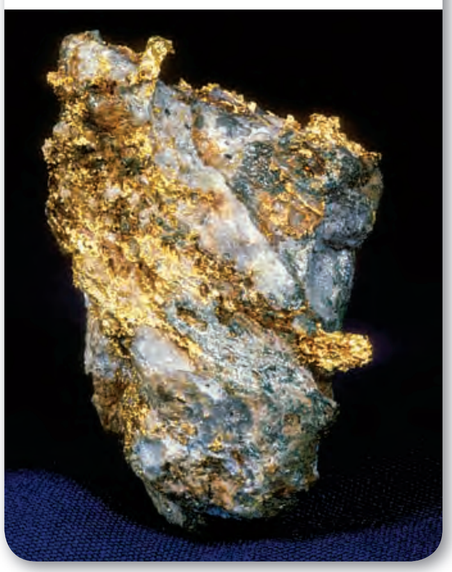
Igneous Rocks as Resources

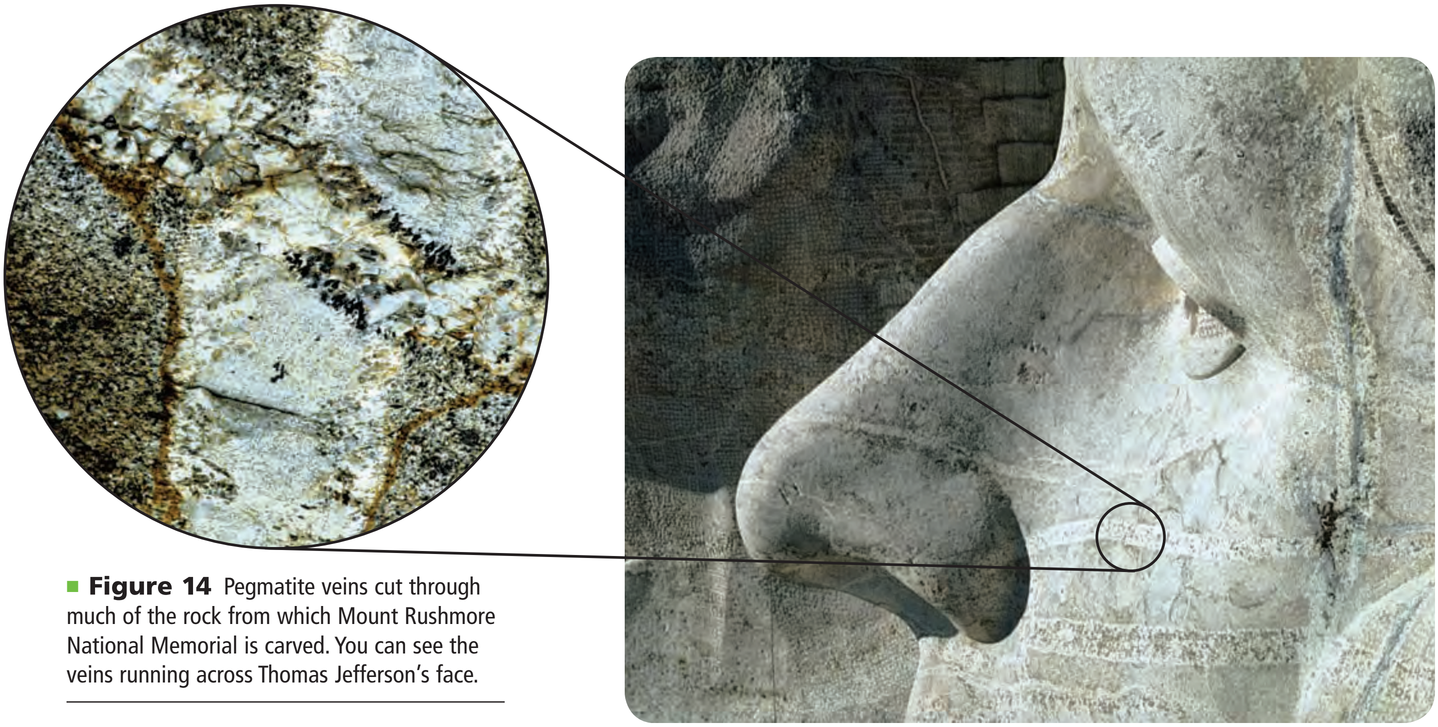
The cooling and crystallization history of igneous rocks sometimes results in the formation of unusual but useful minerals. These minerals can be used in many fields, including construction, energy production, and jewelry making. Some of these uses are described in the following paragraphs.

Veins As you have learned, ores are minerals that contain a useful material that can be mined for a profit. Valuable ore deposits often occur within igneous intrusions. At other times, ore minerals are found in the rocks surrounding intrusions. These types of deposits sometimes occur as veins. Recall from Bowen's reaction series that the fluid left during magma crystallization contains high levels of silica and water. This fluid also contains any leftover elements that were not incorporated into the common igneous minerals. Some important metallic elements that are not included in common minerals are gold, silver, lead, and copper. These elements, along with the dissolved silica, are released at the end of magma crystallization in a hot, mineral-rich fluid that fills cracks and voids in the surrounding rock. This fluid solidifies to form metal-rich quartz veins, such as the gold-bearing veins in the Sierra Nevada. An example of gold formed in a quartz vein is shown in **Figure 13.**

☑ READING CHECK **Explain** why veins have high amounts of quartz.

■ **Figure 13** Gold and quartz are extracted from mines together. The two are later separated.
Infer ***What can you determine from this photo about the melting temperature of gold?***





■ **Figure 14** Pegmatite veins cut through much of the rock from which Mount Rushmore National Memorial is carved. You can see the veins running across Thomas Jefferson's face.

(l)W. K. Fletcher/Photo Researchers, (r)Dave Bartruff/CORBIS

Pegmatites Vein deposits can contain other valuable resources in addition to metals. Veins that are made of extremely large-grained minerals are called **pegmatites.** Ores of rare elements, such as lithium (Li) and beryllium (Be), form in pegmatites. In addition to ores, pegmatites can produce beautiful crystals. Because these veins fill cavities and fractures in rock, minerals grow into voids and retain their shapes. Some of the world's most beautiful minerals have been found in pegmatites. A famous pegmatite is the rock source for the Mount Rushmore National Memorial located near Keystone, South Dakota. A close-up view of President Thomas Jefferson, shown in **Figure 14,** reveals the huge mineral veins that run through the rock.

Problem-Solving LAB

Interpret Scientific Illustrations

How do you estimate mineral composition? Igneous rocks are classified by their mineral compositions. In this activity, you will use the thin section in **Figure 12** to estimate the different percentages of minerals in the sample.

Analysis

1. Design a method to estimate the percentages of the minerals in the rock sample shown in **Figure 12.**
2. Make a data table that lists the minerals and their estimated percentages.

Think Critically

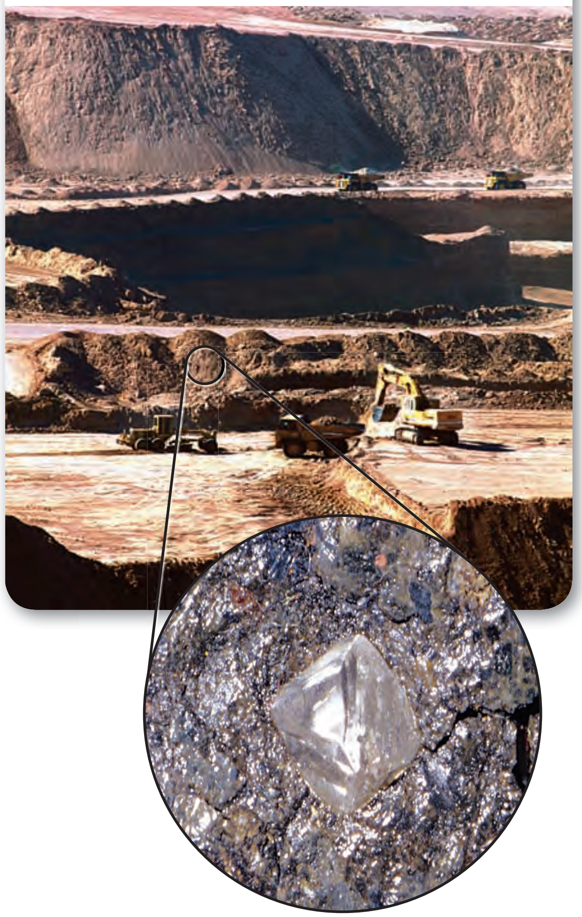
3. **Interpret Figure 9** to determine where in the chart this rock sample fits.
4. **Compare** your estimates of the percentages of minerals in the rock with those of your classmates. Why do the estimates vary? What are some possible sources of error?
5. **Propose** a method to improve the accuracy of your estimate.

Kimberlites Diamond is a valuable mineral found in rare, ultrabasic rocks known as **kimberlites,** named after Kimberly, South Africa, where the intrusions were first identified. These unusual rocks are a variety of peridotite. They most likely form in the mantle at depths of 150 to 300 km. This is because diamonds and other minerals present in kimberlites can form only under very high pressure.

Geologists hypothesize that kimberlite magma is intruded rapidly upward toward Earth's surface, forming long, narrow, pipelike structures. These structures extend many kilometers into the crust, but they are only 100 to 300 m in diameter. For this reason, they are often called kimberlite pipes. Most of the world's diamonds come from South African mines, such as the one shown in **Figure 15.** Many kimberlites have been discovered in the United States, but diamonds have been found only in Arkansas and Colorado. The diamond mine in Colorado is the only diamond mine currently in operation in the United States.

Igneous rocks in construction Igneous rocks have several characteristics that make them especially useful as building materials. The interlocking grain textures of igneous rocks make them strong. In addition, many of the minerals present in igneous rocks are resistant to weathering. Granite is among the most durable of igneous rocks. You have probably seen many items, such as countertops, floors, and statues, made from the wide variety of granite that has formed on Earth.

■ **Figure 15** Diamonds are mined from kimberlite in mines like this one in Richtersveld, Northern Cape, South Africa.



SECTION 2 REVIEW

Section Self-Check

Section Summary

- Igneous rocks are either ultrabasic, basaltic, intermediate, or granitic.
- The rate of cooling determines crystal size.
- Ores often occur in pegmatites. Diamonds occur in kimberlites.
- Some igneous rocks are used as building materials because of their strength, durability, and beauty.

Understand Main Ideas

1. **MAIN**IDEA **Infer** why obsidian, which is black or red in color, can have a granitic composition.
2. **Describe** the three major compositional groups of igneous rocks.
3. **Apply** what you know about cooling rates to explain differences in crystal sizes.
4. **Distinguish** between andesite and diorite using two physical properties of igneous rocks.

Think Critically

5. **Speculate** why there are almost no extrusive ultrabasic rocks in Earth's crust.
6. **Determine** whether quartz or plagioclase feldspar is more likely to form a well-shaped crystal in an igneous rock. Explain.

MATH IN ▶ Earth Science

7. A granite slab has a density of 2.7 g/cm^3. What is the mass of a 2-cm-thick countertop that is 0.6 m $\times$ 2.5 m? How many grams is this?

Earth Science & ENVIRONMENT

Moon Rocks

During each of the six Apollo missions, lunar rocks were collected with the hope of providing information about the Moon's origin, history, and environment. How do moon rocks compare with rocks on Earth?

Moon rock types Between 1969 and 1972, astronauts collected approximately 380 kg of lunar rocks. The 2415 individual pieces range in size from a grain of sand to a basketball.

Generally, moon rocks vary in color from gray to black to white to green. Some rocks are glassy, some are hard, and others are fragile. Analysis of the rocks has revealed at least three different rock types on the Moon. Basaltic rocks formed from lava flows and volcanic ash that reached the surface through cracks and fissures caused by meteorite impacts. Breccias formed when meteorites shattered rocks and then fused the pieces together with the heat generated by the impact. Pristine rock is rock that has not been hit by meteorites. Pristine rock is commonly composed of calcium-rich plagioclase feldspar and is gray in color.

Moon rock composition Moon rocks are unique in two ways. First, they are not oxidized. Considering how much iron is contained in the rocks, this is a sharp contrast to weathered and rusty iron-bearing rocks on Earth. Second, the surfaces of some moon rocks are covered with tiny pockmarks called zap pits. These are caused by micrometeoroids that impact the rocks on the Moon's surface. Zap pits do not occur on Earth rocks because friction from Earth's atmosphere causes tiny meteoroids to burn up long before they reach Earth's surface.

Moon rock classification Scientists use the same categories for classifying lunar rocks as they use for igneous rocks on Earth.

Roger Ressmeyer/CORBIS

This scientist is studying a piece of basalt that was collected from the lunar surface during the *Apollo 15* mission.

Based on mineral composition, scientists named a new class of moon rocks called KREEP rocks. These contain high amounts of potassium (K), rare Earth elements (REE), and phosphorus (P).

Water in moon rocks For over 40 years, scientists thought that the moon was dry. However, in 2010, researchers identified water in lunar rock samples collected during NASA's *Apollo* missions in the 1970s. This water likely came from comets. Scientists continue to pose questions about these rocks as they study the Moon's origin and history.

WRITING IN ▶ Earth Science

Lunar Rock Game Use resources to design a game that involves the collection and analysis of lunar rocks by scientists. Trade games with classmates to increase your understanding of lunar rocks.

WebQuest

GeoLAB

iLab Station

Design Your Own: Model Crystal Formation

Background: The rate at which magma cools affects the grain size of the resulting igneous rock. Observing the crystallization of magma is difficult because molten rock is very hot and the crystallization process is sometimes very slow. Other materials, however, crystallize at lower temperatures. These materials can be used to model crystal formation.

Question: *How do minerals crystallize from magma?*

Materials

clean, plastic petri dishes
saturated alum solution
200-mL glass beaker
magnifying lens
dark-colored construction paper
thermometer
paper towels
water
hot plate

Safety Precautions

WARNING: ***The alum solution can cause skin irritation and will be hot when it is first poured into the petri dishes. If splattering occurs, wash skin with cold water.***

Procedure

1. Read and complete the lab safety form.
2. As a group, plan how you will change the cooling rate of a hot solution poured into a petri dish. Each group member should choose a petri dish in a predetermined location to observe during the investigation. Make sure your teacher approves your plan before you begin.
3. Place a piece of dark-colored construction paper on a level surface where it will not be disturbed. Be sure to put the paper in all of the predetermined locations. Place the petri dishes on top of the paper.
4. Using the glass beaker, obtain about 150 mL of saturated alum solution from your teacher. The temperature should be about 95°C to 98°C, just below boiling temperature.
5. Carefully pour some of the solution into each petri dish so that it is half full. Use caution when pouring the hot liquid to avoid splatters and burns.
6. Every 5 min for 30 min, record your observations of your petri dish. Make drawings of any crystals that begin to form.

Analyze and Conclude

1. **Compare** your methods of cooling with those of other groups. Did some methods appear to work better than others? Explain.
2. **Examine** your alum crystals. What do the crystals look like? Are they all the same size? Do all the crystals have the same shape?
3. **Draw** the most common crystal shape in your science journal. Compare your drawings with those of other groups. Describe any patterns that you see.
4. **Deduce** what factors affected the size of the crystals in the different petri dishes. How do you know?
5. **Infer** why the crystals changed shape as they grew.
6. **Compare and contrast** this experiment with magma crystallization.
7. **Evaluate** the relationship between cooling rate and crystal formation.

SHARE YOUR DATA

Peer Review Post a summary of your data. Compare and contrast your results with those of other students who have completed this lab.

Matt Meadows

CHAPTER 5 STUDY GUIDE

BIGIDEA **Igneous rocks were the first rocks to form as Earth cooled from a molten mass to the crystalline rocks of the early crust.**

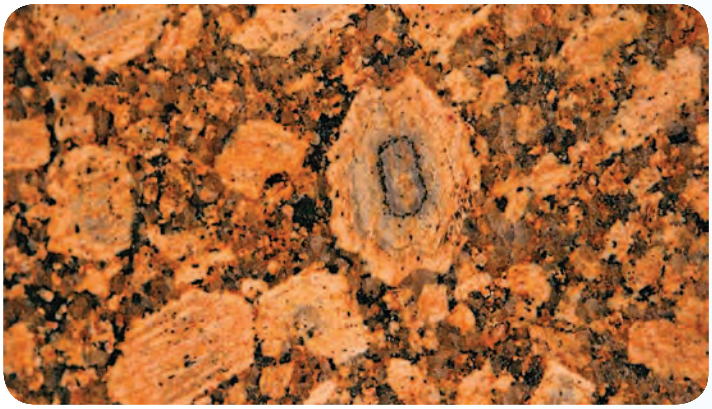
Vocabulary Practice

SECTION 1 What are igneous rocks?

VOCABULARY
- lava
- igneous rock
- partial melting
- Bowen's reaction series
- fractional crystallization

MAINIDEA **Igneous rocks are the rocks that form when molten material cools and crystallizes.**

- Magma consists of molten rock, dissolved gases, and mineral crystals.
- Magma is classified as basaltic, andesitic, or rhyolitic, based on the amount of silica it contains.
- Different minerals melt and crystallize at different temperatures.
- Bowen's reaction series defines the order in which minerals crystallize from magma.



SECTION 2 Classification of Igneous Rocks

VOCABULARY
- intrusive rock
- extrusive rock
- basaltic rock
- granitic rock
- texture
- porphyritic texture
- vesicular texture
- pegmatite
- kimberlite

MAINIDEA **Classification of igneous rocks is based on mineral composition and texture.**

- Igneous rocks are either ultrabasic, basaltic, intermediate, or granitic.
- The rate of cooling determines crystal size.
- Ores often occur in pegmatites. Diamonds occur in kimberlites.
- Some igneous rocks are used as building materials because of their strength, durability, and beauty.

CHAPTER 5 ASSESSMENT

Chapter Self-Check

VOCABULARY REVIEW

The sentences below are incorrect. Make each sentence correct by replacing the italicized word or phrase with a vocabulary term from the Study Guide.

1. Gases escape from *magma* as it flows out onto Earth's surface.

2. *Mohs scale of hardness* describes the order in which minerals crystallize.

3. *Lava* forms deep beneath Earth's crust.

Complete the sentences by filling in the blank with the correct vocabulary term from the Study Guide.

4. An igneous texture characterized by large crystals embedded in a fine-grained background is called a ________.

5. Igneous rocks that form under conditions of fast cooling are said to be ________.

6. Light-colored rocks high in silica are said to be ________.

UNDERSTAND KEY CONCEPTS

7. Which is the first mineral to form in cooling magma?

A. quartz
B. mica
C. potassium feldspar
D. olvine

Use the diagram below to answer Question 8.

8. Which process is occurring in the diagram?

A. fractional separation
B. crystal separation
C. fractional crystallization
D. partial melting

9. Which minerals are associated with the right-hand branch of Bowen's reaction series?

A. olivine and pyroxene
B. feldspars
C. mica and feldspars
D. quartz and biotite

10. Which magma type contains the greatest amount of silica?

A. basaltic
B. andesitic
C. rhyolitic
D. peridotic

11. Which does not affect the formation of magma?

A. volume
B. temperature
C. pressure
D. mineral composition

12. Which intrusive rock has the same composition as andesite?

A. granite
B. basalt
C. obsidian
D. diorite

Use the figure below to answer Question 13.

13. Which process formed this rock?

A. slow cooling
B. fast cooling
C. very fast cooling
D. slow, then fast cooling

14. Which type of ultrabasic rock sometimes contains diamonds?

A. pegmatite
B. kimberlite
C. granite
D. rhyolite

Breck P. Kent/Animals Animals

15. What effect does a fast cooling rate have on grain size in igneous rocks?
    A. It forms fine-grained crystals.
    B. It forms large-grained crystals.
    C. It forms light crystals.
    D. It forms dark crystals.

16. What term describes igneous rocks that crystallize inside Earth?
    A. magma
    B. intrusive
    C. lava
    D. extrusive

17. Which minerals are most common in granite?
    A. quartz and feldspar
    B. plagioclase feldspar and amphibole
    C. olivine and pyroxene
    D. quartz and olivine

CONSTRUCTED RESPONSE

18. **List** some uses of igneous rocks in the construction industry.

19. **Explain** how and why the plagioclase feldspar in basaltic rocks differs from that in granitic rocks.

Use the photos below to answer Questions 20 and 21.

20. **Draw** a flowchart documenting the formation of the holes in this sample of vesicular basalt.

21. **Speculate** on the reasons that samples of pumice are able to float in water.

22. **Illustrate** how fractional crystallization changes the composition of magma, using the formation of iron-rich olivine to illustrate the point.

23. **Apply** the concepts of temperature and crystallization to explain why magma is often described as a slushy mixture of crystals and molten rock.

Use the table below to answer Questions 24 and 25.

Rock Composition

Mineral	Mineral Percentage			
	Rock 1	Rock 2	Rock 3	Rock 4
Quartz	5	35	0	0
Potassium feldspar	0	15	0	0
Plagioclase feldspar	55	25	0	55
Biotite	15	15	0	10
Amphibole	25	10	0	30
Pyroxene	0	0	40	5
Olivine	0	0	60	0

24. **Analyze** the data in the table, and explain which rock is most likely granite.

25. **Incorporate** Use the data for Rock 4 and the fact that it is fine-grained to determine the name of Rock 4.

THINK CRITICALLY

26. **Compare** obsidian and granite to explain why granite is more easily carved into statues and monuments.

27. **Evaluate** this statement: It is possible for magma to have a higher silica content than the melted rock from which it forms.

28. **Apply** what you know about mineral hardness to explain why stainless steel knives do not harm granite cutting boards.

29. **Infer** Kimberlites are the source of most diamonds. Infer why scientists study kimberlites to learn more about Earth's mantle.

30. **Assess** Rocks generally consist of minerals. When molten rock is chilled rapidly, it becomes a glass. Volcanic glass is an extrusive igneous rock. Assess whether this rock contains minerals. Explain your answer. *[Hint: Recall the definition of a mineral.]*

31. **Infer** why rocks that are composed of minerals that crystallize first according to Bowen's reaction series are unstable and break down quickly at Earth's surface.

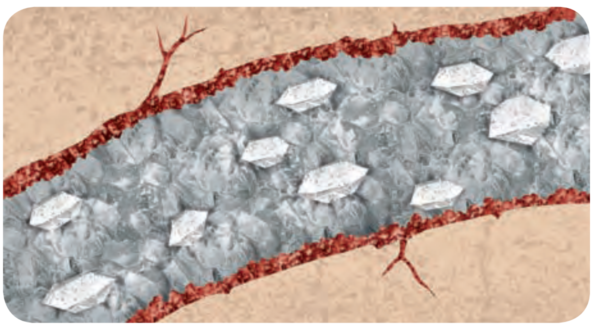
32. **Hypothesize** what the Palisades Sill would look like if the magma that formed it was granitic in composition.

CONCEPT MAPPING

33. Use the following terms to create a concept map showing the relationship among position in Earth's crust and mantle, crystal size, and rock type: *fast, slow, slowest, intrusive, extrusive, magma, lava, granite, rhyolite, basalt, gabbro, obsidian,* and *pumice.*

CHALLENGE QUESTION

Use the diagram below to answer Question 34.



34. **Determine** The diagram shows a cross section of the Leopard Lode, an igneous rock unit in Wyoming. Determine the formation history of this rock unit.

WRITING IN ▸ Earth Science

35. Building stone is expensive. Suppose you are selling kitchen countertops that look like granite, but consist of a less-expensive synthetic material. List the specific characteristics of granite that your customers would look for in the imitation granite.

DBQ Document–Based Questions

Data obtained from: Gerya, T.V., et al. 2003. Cold fingers in a hot magma: numerical modeling of country-rock diapirs in the Bushveld Complex, South Africa. *Geology* 31 (9): 753.

The Bushveld Complex is the world's largest layered intrusion. It was injected as a hot, dense basaltic magma between overlying volcanic and underlying sedimentary rocks. Modeling of this event indicates that finger-shaped bodies of heated, metamorphosed sedimentary rocks subsequently intruded the overlying igneous layers. The model assumed the igneous rock properties shown in the table.

Igneous Rock Properties

Rock Type	Density (kg/m^3)	T Solidus (°C)	T Liquidus (°C)
Granitic	2700 (solid) 2400 (molten)	675	925
Basaltic/ ultrabasic	3000 (solid) 2900 (molten)	950	1100

36. Compare and contrast the density of solid and molten rocks in this model.

37. Speculate about why the overlying rhyolitic rocks could not penetrate, or sink into, the basaltic magma.

38. Infer the meaning of the terms *liquidus* and *solidus.* At what temperature do the first crystals in granitic rocks melt?

CUMULATIVE REVIEW

39. What is a molecule? **(Chapter 3)**

40. Name a gemstone that consists of corundum. **(Chapter 4)**

MULTIPLE CHOICE

Use the table below to answer Questions 1 and 2.

Characteristics of Rocks			
	Color	Silica Content	Composition
Rock A	light	high	quartz and feldspars
Rock B	dark	low	iron and magnesium

1. Rock A is most likely what kind of rock?
A. granitic
B. basaltic
C. ultrabasic
D. intermediate

2. Which of the following is Rock B?
A. granite
B. diorite
C. gabbro
D. rhyolite

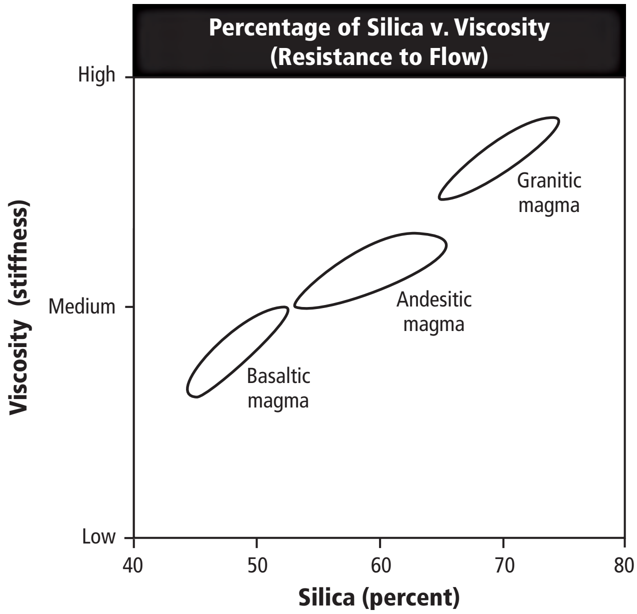
3. Which is most abundant in magma and has the greatest effect on its characteristics?
A. O
B. Ca
C. Al
D. SiO_2

4. Which process describes how minerals in igneous rocks form in predictable sequences?
A. partial melting
B. fractional crystallization
C. Bowen's reaction series
D. geothermal gradient

5. Which is NOT a feature used for identifying minerals?
A. hardness
B. color
C. density
D. volume

6. Which is distorted on a Mercator projection map?
A. shapes of the landmasses
B. areas of the landmasses
C. latitude lines
D. longitude lines

Use the graph below to answer Questions 7 and 8.



7. What relationship can be inferred from the graph?
A. Magmas that have more silica are more viscous.
B. Magmas that have less silica are more viscous.
C. Magmas always have low viscosity.
D. There is no relationship between silica content and viscosity (resistance to flow).

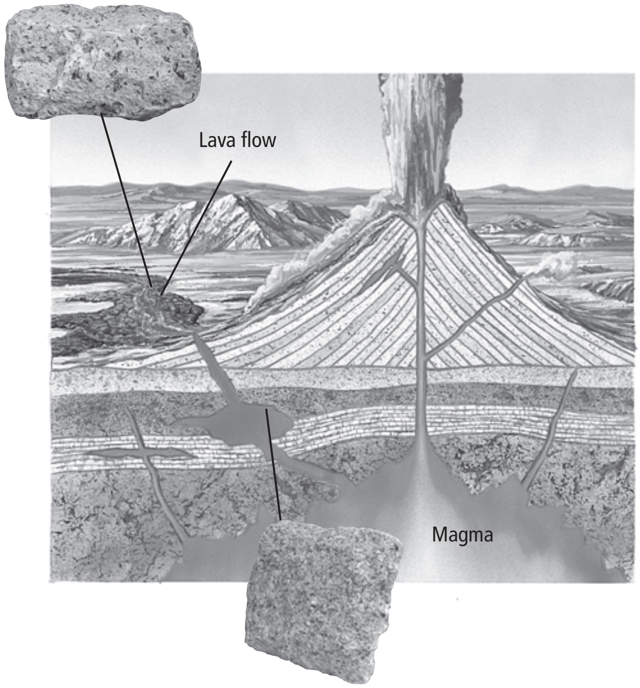
8. Which is a true statement about rhyolitic magma?
A. Rhyolitic magma is heavier than the other two types of magma.
B. Rhyolitic magma is lighter than the other two types of magma.
C. Rhyolitic magma flows more quickly than the other two types of magma.
D. Rhyolitic magma flows more slowly than the other two types of magma.

9. Which is a combination of two or more components that retain their identities?
A. chemical **C.** mixture
B. solution **D.** element

10. Which is the lightest of all atoms?
A. uranium atom **C.** carbon atom
B. oxygen atom **D.** hydrogen atom

SHORT ANSWER

Use the picture below to answer Questions 11–13.



11. What type of igneous rock is located at the bottom of the picture? State a common example of that type of rock and explain how that rock is formed.

12. What type of igneous rock is located at the top of the picture? State a common example of that type of rock and explain how that type of rock is formed.

13. Contrast the formation of the two types of igneous rock.

14. What does it mean to say that minerals are naturally occurring and inorganic?

15. Why are some minerals classified as gems?

16. Why are both latitude and longitude lines necessary when identifying a location?

READING FOR COMPREHENSION

Mariana Island Research

Billowing ash plumes, molten sulfur droplets, feisty shrimp feasting on fish killed by noxious gases, and red lava jetting from a vent are all part of the action recently filmed at an underwater volcano in the western Pacific Ocean. The images are the first ever direct observations of an active, submarine-arc volcano. Unlike volcanic activity at mid-ocean ridges, island-arc volcanoes can remain fixed over their magma sources for thousands of years, allowing them to sometimes grow above water level and become islands. The new studies at the Mariana Islands are giving scientists a firsthand look into this formation process. The volcano has been going through nearly constant low-level eruptions since at least 2004, when it was first observed, Embley says. It could potentially keep erupting for decades, giving scientists the opportunity to monitor its growth.

Article obtained from: Roach, J. "Deep-Sea Volcano Erupts on Film—A First" *National Geographic News.* 24 May 2006.

17. What are the benefits of the new studies at the Mariana Islands?
    - **A.** The studies give scientists a firsthand look into the formation process.
    - **B.** The studies reveal that the volcano could potentially keep erupting for decades.
    - **C.** The studies show life near the vent.
    - **D.** The studies are the first ever direct observations of an active submarine arc-volcano.

18. What can you infer from this passage?
    - **A.** Volcanoes constantly erupt at some level of intensity.
    - **B.** Volcanic activity occurs only at mid-ocean ridges.
    - **C.** Fish and shrimp can live near underwater volcanoes.
    - **D.** There are many active submarine volcanoes.

NEED EXTRA HELP?

If You Missed Question . . .	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Review Section . . .	5.2	5.2	5.1	5.1	4.1	2.2	5.1	5.1	3.2	3.1	5.2	5.2	5.2	4.1	4.2	2.1

CHAPTER 6

Sedimentary and Metamorphic Rocks

BIGIDEA **Most rocks are formed from preexisting rocks through external and internal geologic processes.**

SECTIONS

1 Formation of Sedimentary Rocks

2 Types of Sedimentary Rocks

3 Metamorphic Rocks

LaunchLAB

iLab Station

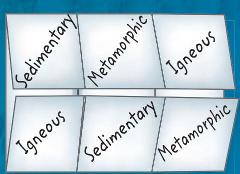
What happened here?

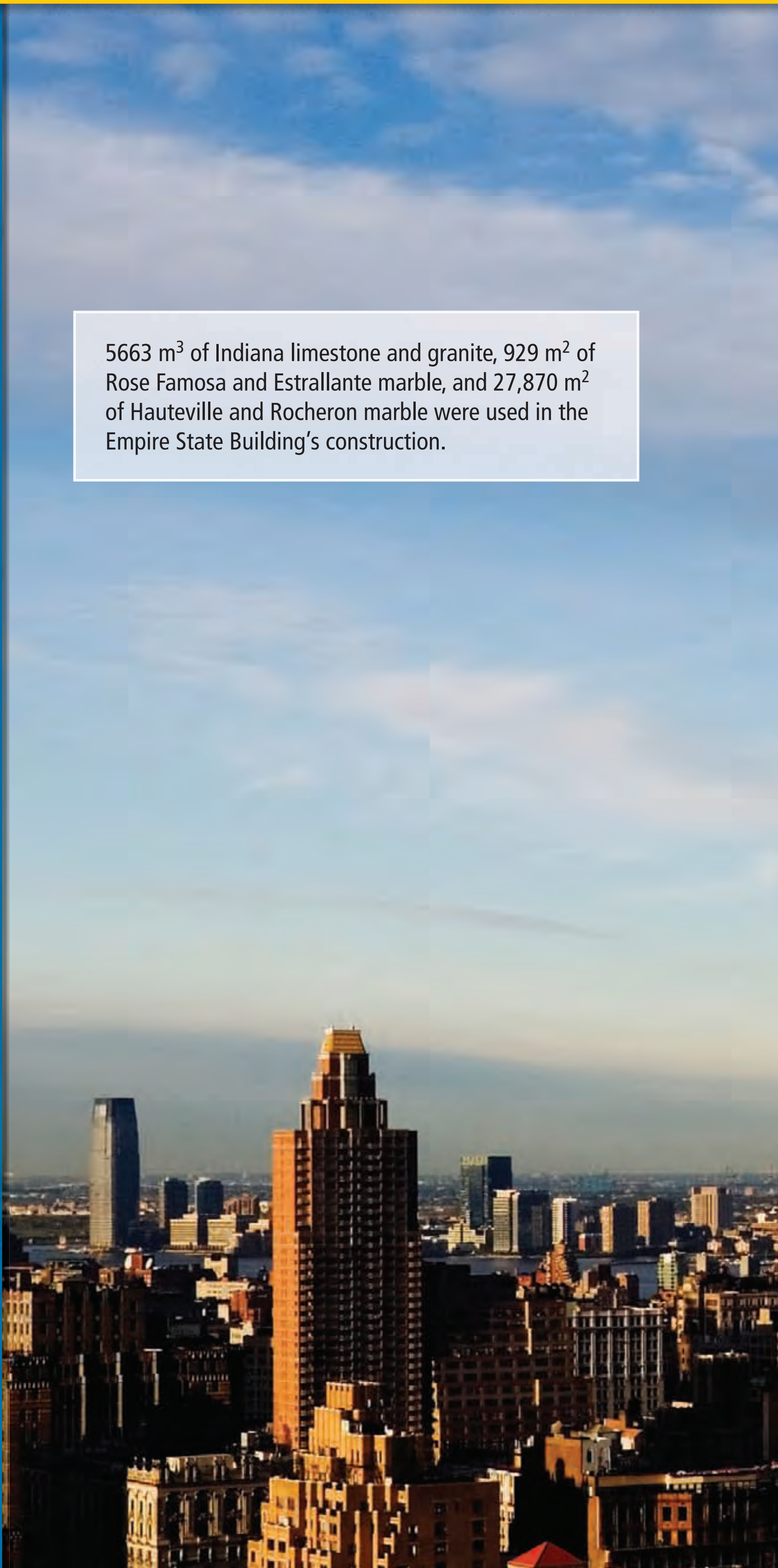
Fossils are the remains and traces of once-living plants and animals. In this activity, you will interpret animal activity from the pattern of fossil footprints.

FOLDABLES® Study Organizer

The Rock Cycle

Make a six-door book using the labels shown. Use it to show possible paths of rock formation.





5663 m^3 of Indiana limestone and granite, 929 m^2 of Rose Famosa and Estrallante marble, and 27,870 m^2 of Hauteville and Rocheron marble were used in the Empire State Building's construction.

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SECTION 1

Formation of Sedimentary Rocks

MAINIDEA **Sediments produced by weathering and erosion form sedimentary rocks through the process of lithification.**

Essential Questions

- How are sedimentary rocks formed?
- What is the process of lithification?
- What are the main features of sedimentary rocks?

Review Vocabulary

texture: the physical appearance or feel of a rock

New Vocabulary

sediment
lithification
cementation
bedding
graded bedding
cross-bedding

EARTH SCIENCE 4 YOU

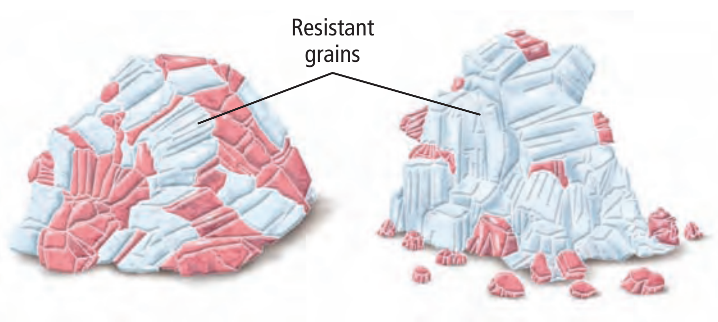
Whenever you are outside, you might see pieces of broken rock, sand, and soil on the ground. What happens to this material? With one heavy rain, these pieces of broken rock, sand, and soil could be on their way to becoming part of a sedimentary rock.

Weathering and Erosion

Wherever rock is exposed at Earth's surface, it is continuously being broken down by weathering—a set of physical and chemical processes that breaks rock into smaller pieces. **Sediments** are small pieces of rock that are moved and deposited by water, wind, glaciers, and gravity. When sediments become glued together, they form sedimentary rocks. The formation of sedimentary rocks begins when weathering and erosion produce sediments.

Weathering Weathering produces rock and mineral fragments known as sediments. These sediments range in size from huge boulders to microscopic particles. Chemical weathering occurs when the minerals in a rock are dissolved or otherwise chemically changed. What happens to more-resistant minerals during weathering? While the less-stable minerals are chemically broken down, the more-resistant grains are broken off of the rock as smaller grains. During physical weathering, however, minerals remain chemically unchanged. Rock fragments break off of the solid rock along fractures or grain boundaries. The rock in **Figure 1** has been chemically and physically weathered.

■ **Figure 1** When exposed to both chemical and physical weathering, granite eventually breaks apart and might look like the decomposed granite shown here.
Infer ***which of the three common minerals —quartz, feldspar and mica—will be most resistant to chemical weathering.***



Adrienne Gibson/Animals Animals

Erosion The removal and transport of sediment is called erosion. **Figure 2** shows the four main agents of erosion: wind, moving water, gravity, and glaciers. Glaciers are large masses of ice that move across land. Visible signs of erosion are all around you. For example, water in streams becomes muddy after a storm because eroded silt and clay-sized particles have been mixed in it. You can observe erosion in action when a gust of wind blows soil across the infield at a baseball park. The force of the wind removes the soil and carries it away.

After rock fragments and sediments have been weathered out of the rock, they often are transported to new locations through the process of erosion. Eroded material is almost always carried downhill. Although wind can sometimes carry fine sand and dust to higher elevations, particles transported by water are almost always moved downhill. Eventually, even windblown dust and fine sand are pulled downhill by gravity.

☑ READING CHECK **Summarize** what occurs during erosion.

■ **Figure 2** Rocks and sediment are weathered and transported by the main agents of erosion—wind, moving water, gravity, and glaciers.

MiniLAB

iLab Station

Model Sediment Layering

How do layers form in sedimentary rocks? Sedimentary rocks usually form in layers. In this activity, you will investigate how layers form from particles that settle in water.

Procedure

1. Read and complete the lab safety form.
2. Obtain 50 mL of **sediment** from a location specified by your teacher.
3. Place the sediment in a **200 mL jar with a lid.**
4. Add **water** to the jar until it is three-fourths full.
5. Place the lid on the jar securely.
6. Pick up the jar with both hands and turn it upside down several times to mix the water and sediment. Hesitate briefly with the jar upside down before tipping it up for the last time. Place the jar on a flat surface.
7. Let the jar sit for about 5 min.
8. Observe the settling process.

Analysis

1. **Illustrate** what you observed in a diagram.
2. **Describe** what types of particles settle out first. Explain.
3. **Describe** what types of particles form the topmost layers. Explain.

Deposition When transported sediments are deposited on the ground or sink to the bottom of a body of water, deposition occurs. During the MiniLab, what happened when you stopped turning the jar full of sediment and water? The sediment sank to the bottom and was deposited in layers with the largest grains at the bottom and the smallest grains at the top. Similarly, sediments in nature are deposited when transport stops. Perhaps the wind stops blowing or a river enters a quiet lake or an ocean. In each case, the particles being carried will settle out, forming layers of sediment with the largest grains at the bottom.

Energy of transporting agents Fast-moving water can transport larger particles better than slow-moving water. As water slows down, the largest particles settle out first, then the next largest, and so on, so that different-sized particles are sorted into layers. Such deposits are characteristic of sediment transported by water and wind. Wind, however, can move only small grains. For this reason, sand dunes are commonly made of fine, well-sorted sand, as shown in **Figure 3.** Not all sediment deposits are sorted. Glaciers, for example, move all materials with equal ease. Large boulders, sand, and mud are all carried along by the ice and dumped in an unsorted pile as the glacier melts. Landslides create similar deposits when sediment moves downhill in a jumbled mass.

Lithification

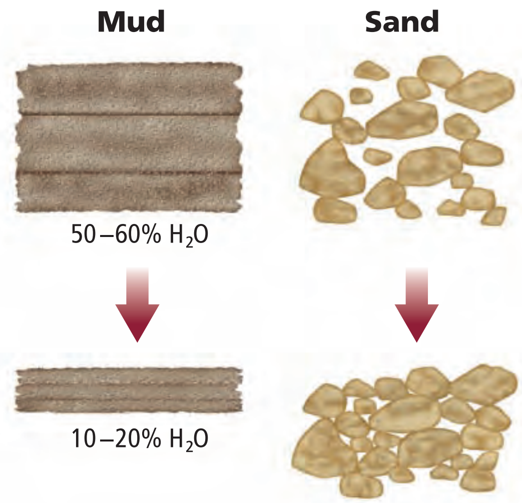
Most sediments are ultimately deposited on Earth in low areas such as valleys and ocean basins. As more sediment is deposited in an area, the bottom layers are subjected to increasing pressure and temperature. These conditions cause **lithification,** the physical and chemical processes that transform sediments into sedimentary rocks. *Lithify* comes from the Greek word *lithos*, which means *stone.*

Figure 3 These sand dunes at White Sands National Monument in New Mexico were formed by windblown sand that has been transported and redeposited. Notice the uniform size of the sand grains.

(l)George Diebold Photography/Iconica/Getty Images, (r)Eastcott Momatiuk/National Geographic/Getty Images

Compaction Lithification begins with compaction. The weight of overlying sediments forces the sediment grains closer together, causing the physical changes shown in **Figure 4.** Layers of mud can contain up to 60 percent water, and these shrink as excess water is squeezed out. Sand does not compact as much as mud during burial. One reason is that individual sand grains, usually composed of quartz, do not deform under normal burial conditions. Grain-to-grain contacts in sand form a supporting framework that helps maintain open spaces between the grains. Groundwater, oil, and natural gas are commonly present in these spaces in sedimentary rocks.

Cementation Compaction is not the only force that binds the grains together. **Cementation** occurs when mineral growth glues sediment grains together into solid rock. This occurs when a new mineral, such as calcite ($CaCO_3$) or iron oxide (Fe_2O_3), grows between sediment grains as dissolved minerals precipitate out of groundwater. This process is illustrated in **Figure 5.**



■ **Figure 4** The high water content and flat shape of particles in mud cause it to compact greatly when subjected to the weight of overlying sediments.

Sedimentary Features

Just as igneous rocks contain information about the history of their formation, sedimentary rocks also have features and characteristics that help geologists interpret how they formed and the history of the area in which they formed.

Bedding The primary feature of sedimentary rocks is horizontal layering called **bedding.** This feature results from the way sediment settles out of water or wind. Individual beds can range in thickness from a few millimeters to several meters. There are two different types of bedding, each dependent upon the method of transport. However, the size of the grains and the material within the bedding depend upon many other factors.

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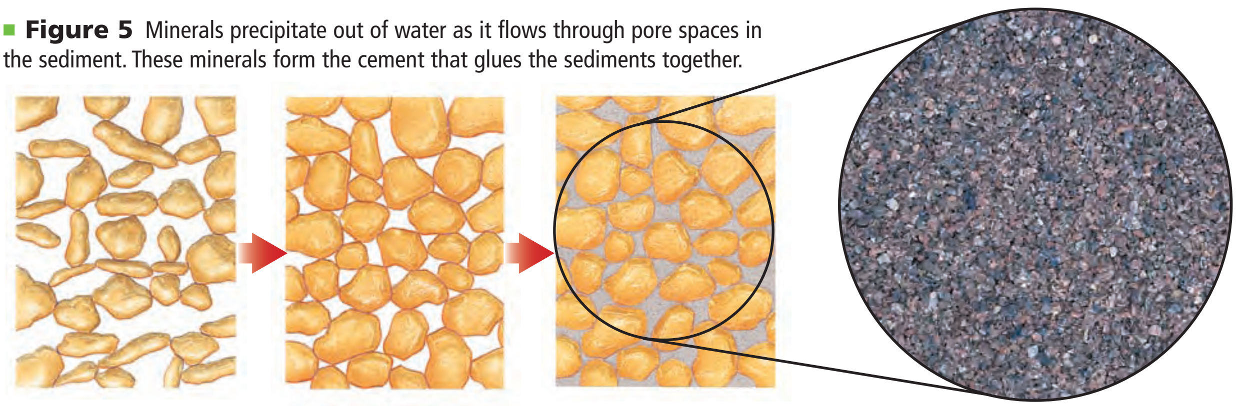
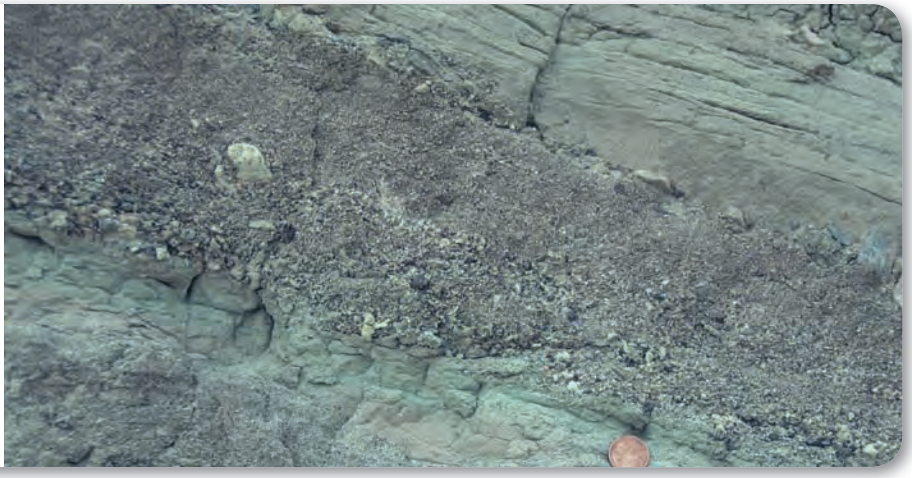
■ **Figure 5** Minerals precipitate out of water as it flows through pore spaces in the sediment. These minerals form the cement that glues the sediments together.



Albert J Copley/Getty Images



■ **Figure 6** The graded bedding shown in this close-up of the Furnace Creek Formation in Death Valley, California, records an episode of deposition during which the water that carried these sediments slowed and lost energy.

Graded bedding Bedding in which the particle sizes become progressively finer and lighter toward the top layers is called **graded bedding.** Graded bedding is often observed in marine sedimentary rocks that were deposited by underwater landslides. As the sliding material slowly came to rest underwater, the largest and heaviest material settled out first and was followed by progressively finer material. An example of graded bedding is shown in **Figure 6.**

CAREERS IN EARTH SCIENCE

Sedimentologist Studying the origin and deposition of sediments and their conversion to sedimentary rocks is the job of a sedimentologist. Sedimentologists are often involved in searching for and finding oil, natural gas, and economically important minerals.

WebQuest

Cross-bedding Another characteristic feature of sedimentary rocks is cross-bedding. **Cross-bedding,** such as that shown in **Figure 7,** is formed as inclined layers of sediment are deposited across a horizontal surface. When these deposits become lithified, the cross-beds are preserved in the rock. This process is illustrated in **Figure 8.** Small-scale cross-bedding forms on sandy beaches and along sandbars in streams and rivers. Most large-scale cross-bedding is formed by migrating sand dunes.

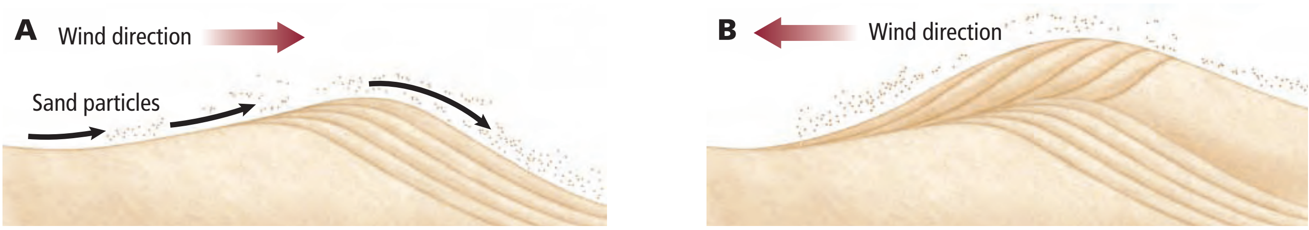
Ripple marks When sediment is moved into small ridges by wind or wave action or by a river current, ripple marks form. The back-and-forth movement of waves forms ripples that are symmetrical, while a current flowing in one direction, such as in a river or stream, produces asymmetrical ripples. If a rippled surface is buried gently by more sediment without being disturbed, it might later be preserved in solid rock. The formation of ripple marks is illustrated in **Figure 8.**

■ **Figure 7** The large-scale cross-beds in these ancient dunes at Zion National Park were deposited by wind.

VISUALIZING Cross-Bedding and Ripple Marks

Figure 8 Moving water and loose sediment result in the formation of sedimentary structures such as cross-bedding and ripple marks.

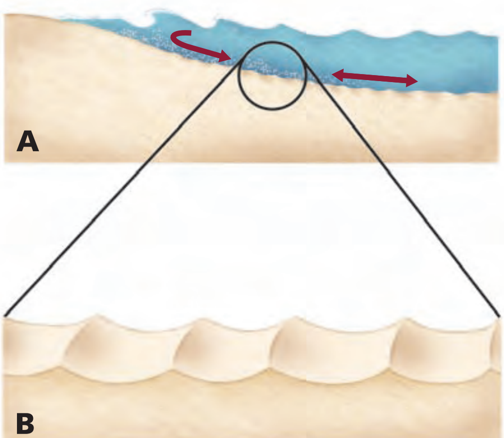
Cross-Bedding



Sand carried by wind gets deposited on the downwind side of a dune. As the wind changes direction, cross-bedding is formed that records this change in direction.

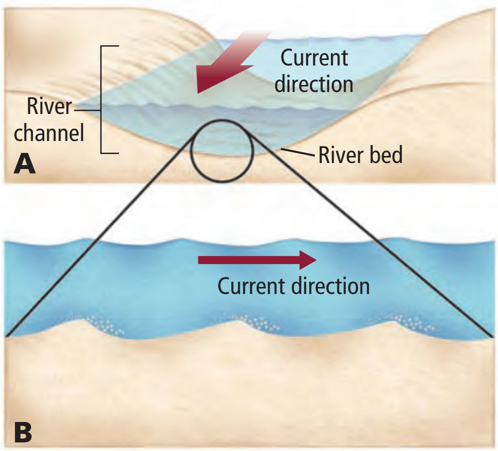
Sediment on the river bottom gets pushed into small hills and ripples by the current. Additional sediment gets deposited at an angle on the downcurrent side of these hills forming cross-beds. Eventually, it levels out or new hills form and the process begins again.

Symmetrical Ripple Marks



The back-and-forth wave action on a shore pushes the sand on the bottom into symmetrical ripple marks. Grain size is evenly distributed.

Asymmetrical Ripple Marks



Current that flows in one direction, such as that of a river, pushes sediment on the bottom into asymmetrical ripple marks. They are steeper upstream and contain coarser sediment on the upstream side.

Concepts In Motion View an **animation of cross-bedding and ripple marks.**

■ **Figure 9** The carbonate sand has sharp, jagged pieces and is not as rounded and smooth as the quartz sand.

Angular vs. rounded Close examination of individual sediment grains reveals that some have jagged, angular edges and some are rounded. When a rock breaks apart, the pieces are initially angular in shape. As the sediment is transported away from its source, individual pieces knock into each other. The edges are broken off and, over time, the pieces become rounded. Thus the amount of rounding is influenced by how long the sediment has been in transport, and consequently, how far the sediment has traveled. Additionally, harder minerals with little to no cleavage have a better chance of becoming rounded before they break apart. As shown in **Figure 9,** quartz sand on beaches is nearly round while carbonate sand, which is made up of seashells and calcite, is usually more angular because it is deposited closer to the source of the sediment.

Evidence of past life Probably the best-known features of sedimentary rocks are fossils. Fossils are the preserved remains, impressions, or any other evidence of once-living organisms. When an organism dies, if its remains are buried without being disturbed, it might be preserved as a fossil. During lithification, parts of the organism can be replaced by minerals and turned into rock, such as shells that have been mineralized. Fossils are of great interest to Earth scientists because fossils provide evidence of the types of organisms that lived in the distant past, the environments that existed in the past, and how organisms have changed over time. You learned first-hand how fossils can be used to interpret past events when you completed the Launch Lab at the beginning of this chapter.

SECTION 1 REVIEW

Section Self-Check

Section Summary

- The processes of weathering, erosion, deposition, and lithification form sedimentary rocks.
- Sediments are lithified into rock by the processes of compaction and cementation.
- Fossils are the remains or other evidence of once-living organisms that are often preserved in sedimentary rocks.
- Sedimentary rocks might contain features such as horizontal bedding, cross-bedding, and ripple marks.

Understand Main Ideas

1. MAINIDEA **Describe** how sediments are produced by weathering and erosion.
2. **Sequence** Use a flowchart to show why sediment deposits tend to form layers.
3. **Illustrate** the formation of graded bedding.
4. **Compare** temperature and pressure conditions at Earth's surface and below Earth's surface, and relate them to the process of lithification.

Think Critically

5. **Evaluate** this statement: It is possible for a layer of rock to show both cross-bedding and graded bedding.
6. **Determine** whether you are walking upstream or downstream along a dry mountain stream if you notice that the shape of the sediment is getting more angular as you continue walking. Explain.

WRITING IN ▶ Earth Science

7. Imagine you are designing a display for a museum based on a sedimentary rock that contains fossils of corals and other ocean-dwelling animals. Draw a picture of what this environment might have looked like, and write the accompanying description that will be posted next to the display.

(t)Rick Poley/Visuals Unlimited, (b)E. R. Degginger/Photo Researchers

SECTION 2

Types of Sedimentary Rocks

MAINIDEA Sedimentary rocks are classified by their mode of formation.

Essential Questions

- How can the different types of clastic sedimentary rocks be described?
- How do chemical sedimentary rocks form?
- What are biochemical sedimentary rocks?

Review Vocabulary

saturated: the maximum possible content of dissolved minerals in solution

New Vocabulary

clastic sedimentary rock
clastic
porosity
evaporite

EARTH SCIENCE 4 YOU **If you have ever walked along the beach or along a riverbank, you might have noticed different sizes of sediments. The grain size of the sediment determines what type of sedimentary rock it can become.**

Clastic Sedimentary Rocks

The most common sedimentary rocks, **clastic sedimentary rocks,** are formed from the abundant deposits of loose sediments that accumulate on Earth's surface. The word **clastic** comes from the Greek word *klastos,* meaning *broken*. These rocks are further classified according to the sizes of their particles. As you read about each rock type, refer to **Table 1** on the next page, which summarizes the classification of sedimentary rocks based on grain size, mode of formation, and mineral content.

Coarse-grained rocks Sedimentary rocks consisting of gravel-sized rock and mineral fragments are classified as coarse-grained rocks, samples of which are shown in **Figure 10.** Conglomerates have rounded, gravel-sized particles. Because of its relatively large mass, gravel is transported by high-energy flows of water, such as those generated by mountain streams, flooding rivers, some ocean waves, and glacial meltwater. During transport, gravel becomes abraded and rounded as the particles scrape against one another. This is why beach and river gravels are often well rounded. Lithification turns these sediments into conglomerates.

In contrast, breccias are composed of angular, gravel-sized particles. The angularity indicates that the sediments from which they formed did not have time to become rounded. This suggests that the particles were transported only a short distance and deposited close to their source. Refer to **Table 1** to see how these rocks are named.

Figure 10 Conglomerates and breccias are made of coarse sediments that have been transported by high-energy water.
Infer *the circumstances that might cause the types of transport necessary for each to form.*

Breck P. Kent/Animals Animals

Explore **sedimentary rock formation with an interactive table.** Concepts In Motion

Table 1 Classification of Sedimentary Rocks

Classification	Texture/Grain Size	Composition	Rock Name
Clastic	coarse (> 2 mm)	Fragments of any rock type—quartz, chert and quartzite common } rounded / angular	conglomerate breccia
	medium (1/16 mm to 2 mm)	quartz and rock fragments quartz, potassium feldspar and rock fragments	sandstone arkose
	fine (1/256 mm–1/16 mm)	quartz and clay	siltstone
	very fine (< 1/256 mm)	quartz and clay	shale
Biochemical	microcrystalline with conchoidal fracture	calcite ($CaCO_3$) quartz (SiO_2)	micrite chert
	abundant fossils in micrite matrix	calcite ($CaCO_3$)	fossiliferous limestone
	shells and shell fragments loosely cemented	calcite ($CaCO_3$)	coquina
	microscopic shells and clay	calcite ($CaCO_3$)	chalk
	variously sized fragments	highly altered plant remains, some plant fossils	coal
Chemical	ooids (small spheres of calcium carbonate)	calcite ($CaCO_3$)	oolitic limestone
	fine to coarsely crystalline	calcite ($CaCO_3$)	crystalline limestone
	fine to coarsely crystalline	dolomite $(Ca,Mg)CO_3$ (will effervesce if powdered)	dolostone
	very finely crystalline	quartz (SiO_2)—light colored; dark colored calcite ($CaCO_3$)	chert; flint micrite
	fine to coarsely crystalline	gypsum ($CaSO_4 \bullet 2H_2O$)	rock gypsum
	fine to coarsely crystalline	halite (NaCl)	rock salt

Medium-grained rocks Stream and river channels, beaches, and deserts often contain abundant sand-sized sediments. Sedimentary rocks that contain sand-sized rock and mineral fragments are classified as medium-grained clastic rocks. Refer to **Table1** for a listing of rocks with sand-sized particles. Sandstone usually contains several features of interest to scientists. For example, because ripple marks and cross-bedding indicate the direction of current flow, geologists use sandstone layers to map ancient stream and river channels.

Another important feature of sandstone is its relatively high porosity. **Porosity** is the percentage of open spaces between grains in a rock. Loose sand can have a porosity of up to 40 percent. Some of these open spaces are maintained during the formation of sandstone, often resulting in porosities as high as 30 percent. When pore spaces are connected to one another, fluids can move through sandstone. This feature makes sandstone layers valuable as underground reservoirs of oil, natural gas, and groundwater.

VOCABULARY

ACADEMIC VOCABULARY

Reservoir
a subsurface area of rock that has enough porosity to allow for the accumulation of oil, natural gas, or water
The newly discovered reservoir contained large amounts of natural gas and oil.

Fine-grained rocks Sedimentary rocks consisting of silt- and clay-sized particles, such as siltstone and shale, are called fine-grained rocks. These rocks represent environments like swamps, ponds, and deep oceans which have still or slow-moving waters. In the absence of strong currents and wave action, these sediments settle to the bottom where they accumulate in thin horizontal layers. Shale often breaks along thin layers, as shown in **Figure 11.** Unlike sandstone, fine-grained sedimentary rock has low porosity and often forms barriers that hinder the movement of groundwater and oil. **Table 1** shows how these rocks are named.

READING CHECK **Identify** the types of environments in which fine-grained rocks form.

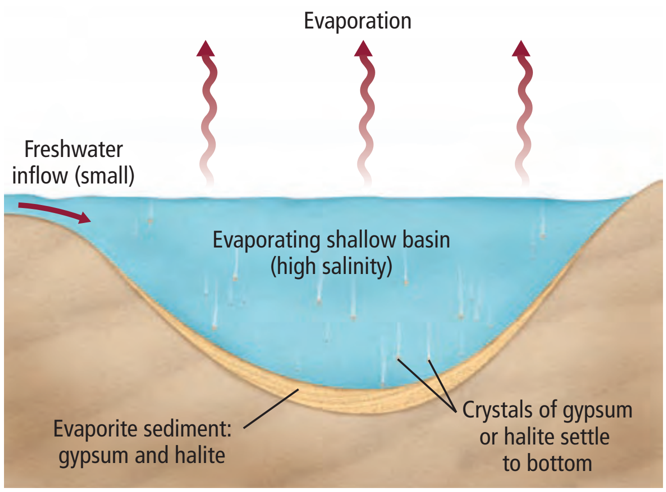
Figure 11 The very fine-grained sediment that formed this shale was deposited in thin layers in still waters.

Chemical and Biochemical Sedimentary Rocks

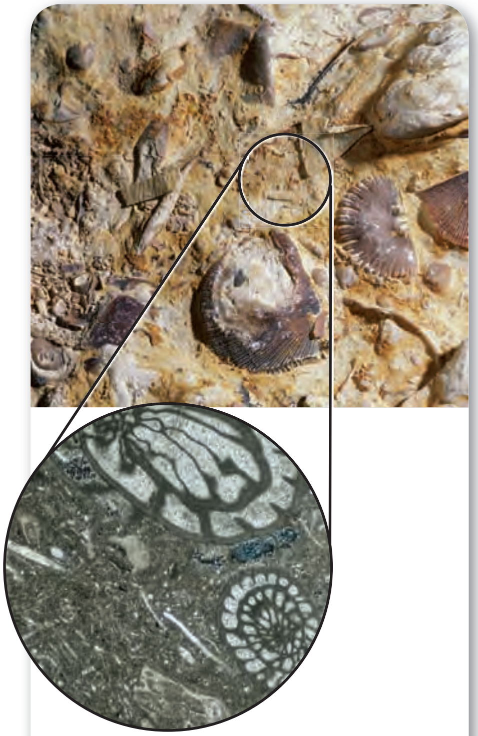
The formation of chemical and biochemical rocks involves the processes of evaporation and precipitation of minerals. During weathering, minerals can be dissolved and carried into lakes and oceans. As water evaporates from the lakes and oceans, the dissolved minerals are left behind. In arid regions, high evaporation rates can increase the concentration of dissolved minerals in bodies of water. The Great Salt Lake, shown in **Figure 12,** is an example of a lake that has high concentrations of dissolved minerals.

Chemical sedimentary rocks When the concentration of dissolved minerals in a body of water reaches saturation, crystals can precipitate out of solution and settle to the bottom. As a result, layers of chemical sedimentary rocks form, most of which are called **evaporites.** Evaporites primarily form in arid regions, drainage basins on continents that have low water flow, and in coastal settings. Because these areas usually have minimal freshwater input and high rates of evaporation, the concentration of dissolved minerals remains high. Over time, thick layers of evaporite minerals can accumulate on basin floors, as illustrated in **Figure 12.**

Figure 12 The constant evaporation from a body of salt water results in precipitation of large amounts of salt. This process has been occurring in the Great Salt Lake in Utah for approximately 18,000 years.



(t)James Steinberg/Photo Researchers, (b)Mary Rhodes/Animals Animals



■ **Figure 13** Limestone can contain many different fossil organisms. Geologists can interpret where and when the limestone formed by studying the fossils within the rock.

Biochemical sedimentary rocks Biochemical sedimentary rocks are formed from the remains of once-living organisms. The most abundant of these rocks is limestone, which is composed primarily of calcite. Some organisms that live in the ocean use the calcium carbonate that is dissolved in seawater to make their shells. When these organisms die, their shells settle to the bottom of the ocean and can form thick layers of carbonate sediment. During burial and lithification, calcium carbonate precipitates out of the water, crystallizes between the grains of carbonate sediment, and forms limestone.

Limestone is common in shallow water environments, such as those in the Bahamas, where coral reefs thrive in 15 to 20 m of water just offshore. The skeletal and shell materials that are currently accumulating there will someday become limestone as well. Many types of limestone contain evidence of their biological origin in the form of abundant fossils. As shown in **Figure 13,** these fossils can range from large-shelled organisms to microscopic, unicellular organisms. However, not all limestone contains fossils or is biochemical in origin. Some limestone has a crystalline texture, or consists of tiny spheres of carbonate sand called ooids. These are listed in **Table 1.**

Other organisms make their shells out of silica, or microcrystalline quartz. After these organisms die and settle to the bottom of the ocean, their shells can form sediment that is often referred to as siliceous ooze because it is rich in silica. Siliceous ooze becomes lithified into the sedimentary rock chert, which is also listed in **Table 1.**

SECTION 2 REVIEW

Section Self-Check

Section Summary

- Sedimentary rocks can be clastic, chemical, or biochemical.
- Clastic rocks form from sediments and are classified by particle size and shape.
- Chemical rocks form primarily from minerals precipitated from water.
- Biochemical rocks form from the remains of once-living organisms.
- Sedimentary rocks provide geologists with information about surface conditions that existed in Earth's past.

Understand Main Ideas

1. MAINIDEA **State** the type of sedimentary rock that is formed from the erosion and transport of rocks and sediments.
2. **Infer** why coal is a biochemical sedimentary rock.
3. **Calculate** the factor by which grain size increases with each texture category.
4. **Analyze** the environmental conditions to explain why most chemical sedimentary rocks form mainly in areas that have high rates of evaporation.

Think Critically

5. **Propose** a scenario to explain how it is possible to form additional layers of evaporites in a body of seawater when the original amount of dissolved minerals in the water was enough to form only a thin evaporite.
6. **Examine** the layers of shale in **Figure 11** and explain why shale contains no cross-bedding or ripple marks.

MATH IN ▶ Earth Science

7. Assume that the volume of a layer of mud will decrease by 35 percent during deposition and compaction. If the original sediment layer is 30 cm thick, what will be the thickness of the shale layer after compaction?

SECTION 3

Metamorphic Rocks

MAINIDEA **Metamorphic rocks form when preexisting rocks are exposed to increases in temperature and pressure and to hydrothermal solutions.**

Essential Questions

- What are the different types and causes of metamorphism?
- How are metamorphic textures described?
- How do mineral and compositional changes occur during metamorphism?
- How are rocks classified using the rock cycle?

Review Vocabulary

intrusive: rocks that form from magma that cooled and crystallized slowly beneath Earth's surface

New Vocabulary

foliated
nonfoliated
regional metamorphism
contact metamorphism
hydrothermal metamorphism
rock cycle

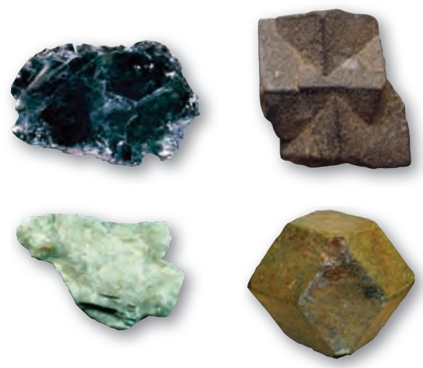
EARTH SCIENCE 4 YOU **When you make a cake, all of the individual ingredients that you put into the pan change into something new. When rocks are exposed to high temperatures, their individual characteristics also change into something new and form a completely different rock.**

Recognizing Metamorphic Rock

The rock layers shown in **Figure 14** have been metamorphosed (meh tuh MOR fohzd)—this means that they have been changed. How do geologists know that this has happened? Pressure and temperature increase with depth. When temperature and pressure becomes high enough, rocks melt and form magma. But what happens if the rocks do not reach the melting point? When temperature and pressure combine and change the texture, mineral composition, or chemical composition of a rock without melting it, a metamorphic rock forms. The word *metamorphism* is derived from the Greek words *meta,* meaning *change*, and *morphé,* meaning *form*. During metamorphism, a rock changes form while remaining solid.

The high temperatures required for metamorphism are ultimately derived from Earth's internal heat, either through deep burial or from nearby igneous intrusions. The high pressures required for metamorphism come from deep burial or from compression during mountain building.

■ **Figure 14** Strong forces were required to bend these rock layers into the shape they are today.
Hypothesize ***the changes that occurred to the sediments after they were deposited.***



■ **Figure 15** Metamorphic minerals, such as mica, staurolite, garnet, and talc (shown above, clockwise from top left), occur in many colors, shapes, and crystal sizes. Colors can be dark or light and crystal form can be unique.

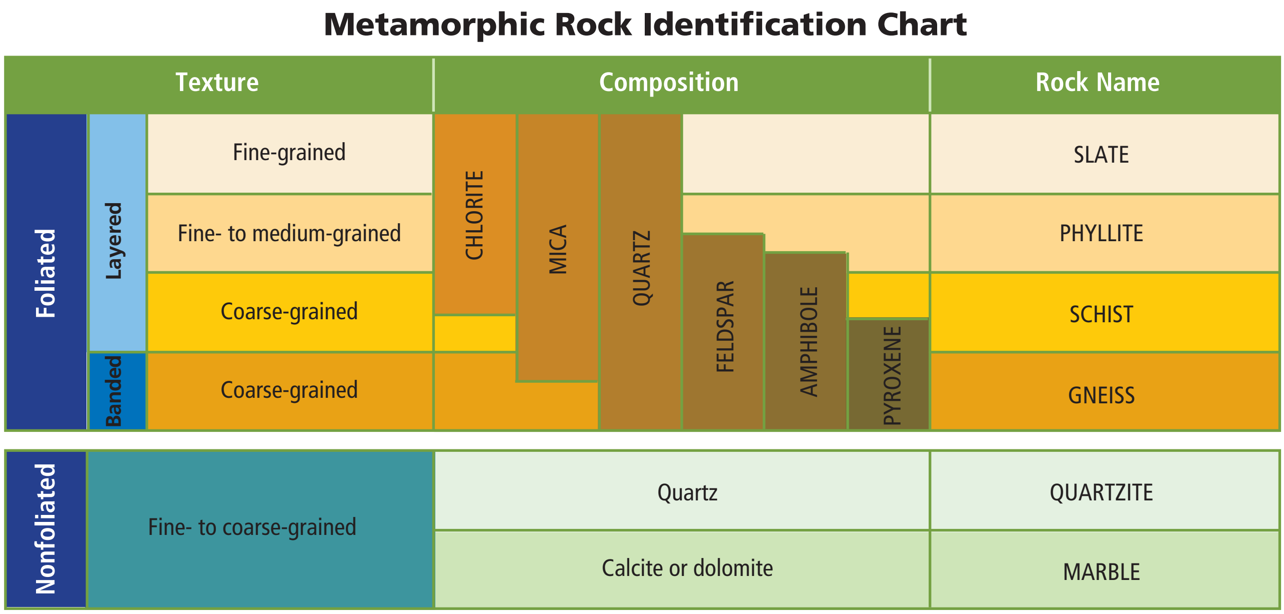
Metamorphic minerals How do minerals change without melting? Think back to the concept of fractional crystallization. Bowen's reaction series shows that all minerals are stable at certain temperatures and they crystallize from magma along a range of different temperatures. Scientists have discovered that these stability ranges also apply to minerals in solid rock. During metamorphism, the minerals in a rock change into new minerals that are stable under the new temperature and pressure conditions. Minerals that change in this way are said to undergo solid-state alterations. Scientists have conducted experiments to identify the metamorphic conditions that create specific minerals. When the same minerals are identified in rocks, scientists are able to interpret the conditions inside the crust during the rocks' metamorphism. **Figure 15** shows some common metamorphic minerals.

☑ READING CHECK **Explain** what metamorphic minerals are.

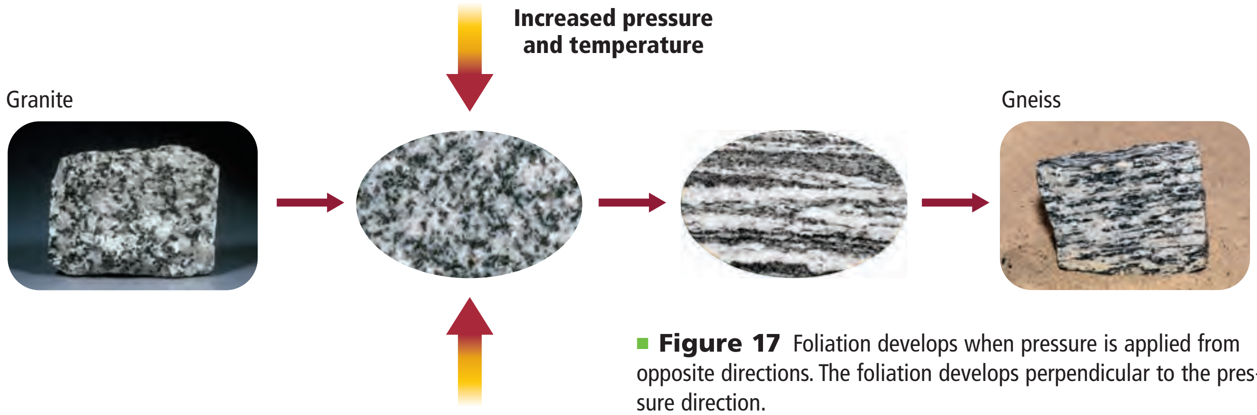
Metamorphic textures Metamorphic rocks are classified into two textural groups: foliated and nonfoliated. Geologists use metamorphic textures and mineral composition to identify metamorphic rocks. **Figure 16** shows how these two characteristics are used in the classification of metamorphic rocks.

Foliated rocks Layers and bands of minerals characterize **foliated** metamorphic rocks. High pressure during metamorphism causes minerals with flat or needlelike crystals to form with their long axes perpendicular to the pressure, as shown in **Figure 17.** This parallel alignment of minerals creates the layers observed in foliated metamorphic rocks.

■ **Figure 16** Increasing grain size parallels changes in composition and development of foliation. Grain size is not a factor in nonfoliated rocks.



(tl)George Whitely/Photo Researchers, (tr)Harry Taylor/Dorling Kindersley/Getty Images, (bl)Biophoto Associates/Photo Researchers, (br)Scientifica/Visuals Unlimited

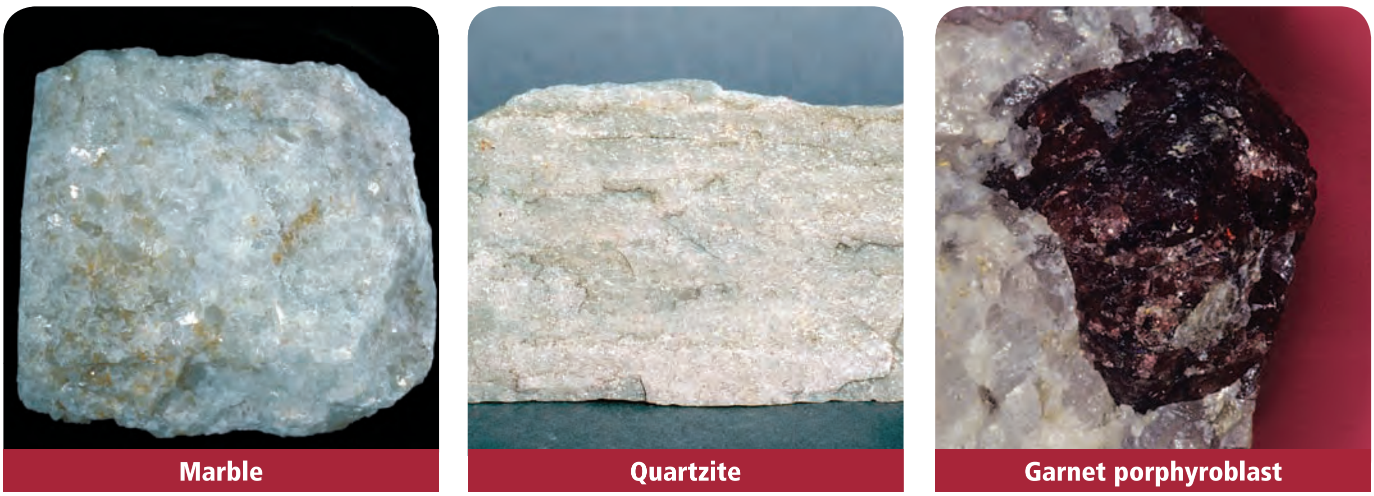


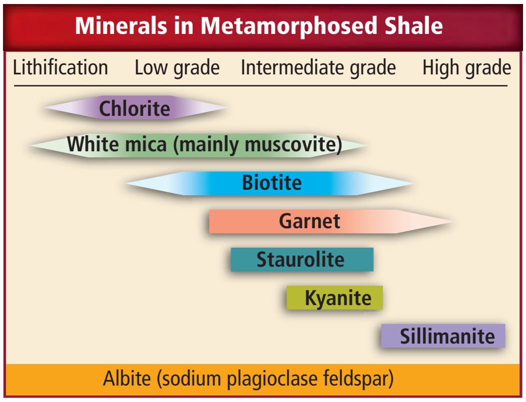
■ **Figure 17** Foliation develops when pressure is applied from opposite directions. The foliation develops perpendicular to the pressure direction.

Nonfoliated rocks Unlike foliated rocks, **nonfoliated** metamorphic rocks are composed mainly of minerals that form with blocky crystal shapes. Two common examples of nonfoliated rocks, shown in **Figure 18,** are quartzite and marble. Quartzite is a hard, often light-colored rock formed by the metamorphism of quartz-rich sandstone. Marble is formed by the metamorphism of limestone or dolomite. Some marbles have smooth textures that are formed by interlocking grains of calcite. These marbles are often used in sculptures. Fossils are rarely preserved in metamorphic rocks.

Under certain conditions, new metamorphic minerals can grow large while the surrounding minerals remain small. The large crystals, which can range in size from a few millimeters to a few centimeters, are called porphyroblasts. Although these crystals resemble the very large crystals that form in pegmatite granite, they are not the same. Instead of forming from magma, they form in solid rock through the reorganization of atoms during metamorphism. Garnet, shown in **Figure 18,** is, a mineral that commonly forms porphyroblasts.

■ **Figure 18** As a result of the extreme heat and pressure during metamorphism, marble rarely contains fossils. Metamorphism does not, however, always destroy cross-bedding and ripple marks, which can be seen in some quartzites. Garnet porphyroblasts can grow to be quite large in some rocks.





■ **Figure 19** Metamorphism of shale results in the formation of minerals that provide the wide variety of color observed in slate.

Grades of Metamorphism

Different combinations of temperature and pressure result in different grades of metamorphism. Low-grade metamorphism is associated with low temperatures and pressures and a particular suite of minerals and textures. High-grade metamorphism is associated with high temperatures and pressures and a different suite of minerals and textures. Intermediate-grade metamorphism is in between low- and high-grade metamorphism.

Figure 19 shows the minerals present in metamorphosed shale. Note the change in composition as conditions change from low-grade to high-grade metamorphism. Geologists can create metamorphic maps by plotting the location of metamorphic minerals. Knowing the temperatures that certain areas experienced when rocks were forming helps geologists locate valuable metamorphic minerals such as garnet and talc. Studying the distribution of metamorphic minerals helps geologists to interpret the metamorphic history of an area.

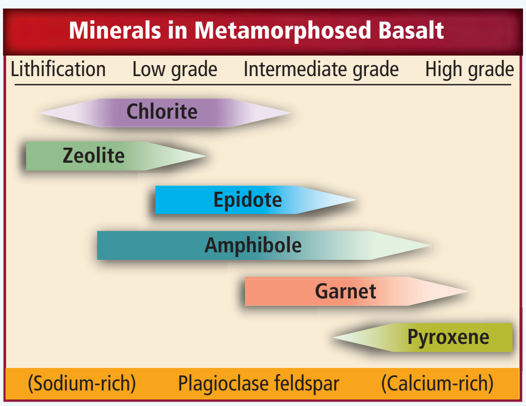
Types of Metamorphism

The effects of metamorphism can be the result of contact metamorphism, regional metamorphism, or hydrothermal metamorphism. The minerals that form and the degree of change in the rocks provide information as to the type and grade of metamorphism that occurred.

Problem-Solving LAB

Interpret Scientific Illustrations

Which metamorphic minerals will form? The minerals that form in metamorphic rocks depend on the metamorphic grade and composition of the original rock. The figure below and **Figure 19** show the mineral groups that form under different metamorphic conditions.

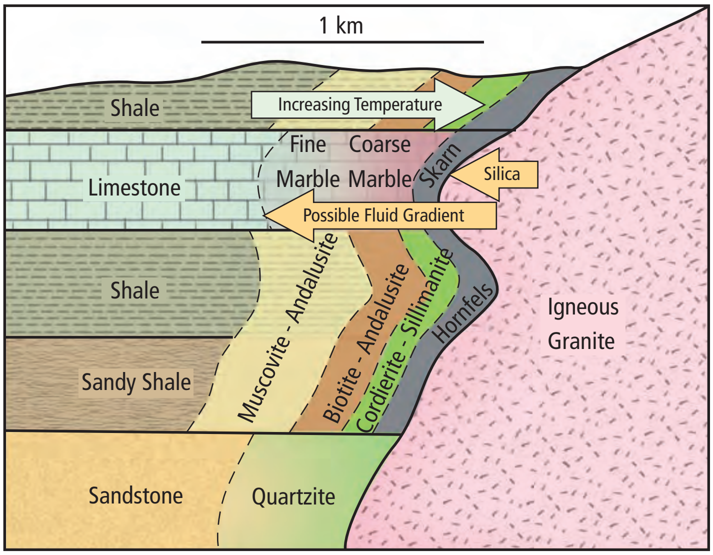


Analysis

1. What minerals are formed when shale and basalt are exposed to low-grade metamorphism?
2. Under high-grade metamorphism, what mineral is formed in shale but not in basalt?

Think Critically

3. **Compare** the mineral groups that you would expect to form from intermediate-grade metamorphism of shale and basalt.
4. **Describe** the major compositional differences between shale and basalt. How are these differences reflected in the minerals formed during metamorphism?
5. **Explain** When limestone is metamorphosed, there is little change in mineral composition. Calcite is still the dominant mineral. Explain why this happens.



■ **Figure 20** Contact metamorphism from the intrusion of this granite batholith has caused zones of metamorphic minerals to form.
Apply ***what you know about contact metamorphism to determine the type of rock that would form if the granite intrusion was metamorphosed.***

Regional metamorphism When temperature and pressure affect large regions of Earth's crust, they produce large belts of **regional metamorphism.** The metamorphism can range in grade from low to high grade. Results of regional metamorphism include changes in minerals and rock types, foliation, and folding and deforming of the rock layers that make up the area. The folded rock layers shown in **Figure 14** experienced regional metamorphism.

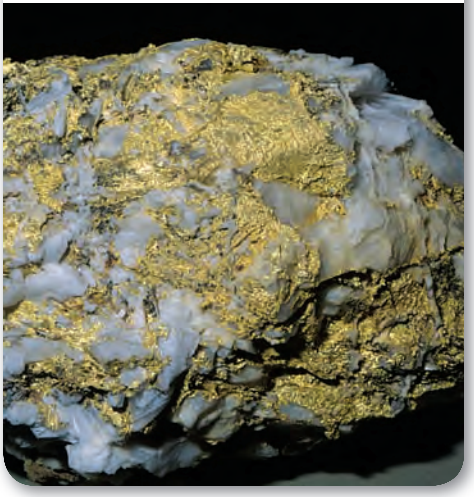
Contact metamorphism When molten material, such as that in an igneous intrusion, comes in contact with solid rock, a local effect called **contact metamorphism** occurs. High temperature and moderate-to-low pressure form mineral assemblages that are characteristic of contact metamorphism. **Figure 20** shows zones of different minerals surrounding an intrusion. Because temperature decreases with distance from an intrusion, metamorphic effects also decrease with distance. Recall that minerals crystallize at specific temperatures. Metamorphic minerals that form at high temperatures occur closest to the intrusion, where it is hottest. Because lava cools too quickly for the heat to penetrate far into surface rocks, contact metamorphism from extrusive igneous rocks is limited to thin zones.

Hydrothermal metamorphism When very hot water reacts with rock and alters its chemical and mineral composition, **hydrothermal metamorphism** occurs. The word *hydrothermal* is derived from the Greek words *hydro,* meaning *water,* and *thermal,* meaning *heat.* As hot fluids migrate in and out of the rock during metamorphism, the original mineral composition and texture of the rock can change. Chemical changes are common during contact metamorphism near igneous intrusions and active volcanoes. Valuable ore deposits of gold, copper, zinc, tungsten, and lead are formed in this manner. The gold deposited in the quartz shown in **Figure 21** is the result of hydrothermal metamorphism.

VOCABULARY
SCIENCE USAGE V. COMMON USAGE
Intrusion
Science usage: the placement of a body of magma into preexisting rock

Common usage: joining or coming into without being invited

■ **Figure 21** When the hydrothermal solution in the quartz cooled, gold veins formed.



Ken Lucas/Visuals Unlimited

Economic Importance of Metamorphic Rocks and Minerals

The modern way of life is made possible by a great number of naturally occurring Earth materials. We need salt for cooking, gold for trade, other metals for construction and industrial purposes, fossil fuels for energy, and rocks and various minerals for construction, cosmetics, and more. **Figure 22** shows two examples of how metamorphic rocks are used in construction. Many of these economic mineral resources are produced by metamorphic processes. Among these are the metals gold, silver, copper, and lead, as well as many significant nonmetallic resources.

Metallic mineral resources Metallic resources occur mostly in the form of metal ores, although deposits of pure metals are occasionally discovered. Many metallic deposits are precipitated from hydrothermal solutions and are either concentrated in veins or spread throughout the rock mass. Native gold, silver, and copper deposits tend to occur in hydrothermal quartz veins near igneous intrusions or in contact metamorphic zones. However, most hydrothermal metal deposits are in the form of metal sulfides such as galena (PbS) or pyrite (FeS_2). The iron ores magnetite and hematite are oxide minerals often formed by precipitation from iron-bearing hydrothermal solutions.

☑ READING CHECK **State** what resources hydrothermal metamorphism produces.

Nonmetallic mineral resources Metamorphism of ultrabasic igneous rocks produces the minerals talc and asbestos. Talc, with a hardness of 1, is used as a dusting powder, as a lubricant, and to provide texture in paints. Because it is not combustible and has low thermal and electric conductivity, asbestos has been used in fireproof and insulating materials. Prior to the recognition of its cancer-causing properties, it was also widely utilized in the construction industry. Many older buildings still have asbestos-containing materials. Graphite, the main ingredient of the lead in pencils, may be formed by the metamorphism of coal.

■ **Figure 22** Marble and slate are metamorphic rocks that have been used in construction for centuries.

(l)Altrendo Travel/Altrendo/Getty Images, (r)Pixtal/SuperStock

The Rock Cycle

Metamorphic rocks form when other rocks change. The three types of rock—igneous, sedimentary, and metamorphic—are grouped according to how they form. Igneous rocks crystallize from magma underneath Earth's surface, or from lava on Earth's surface; sedimentary rocks form from cemented or precipitated minerals and sediments; and metamorphic rocks form from changes in temperature and pressure.

Once a rock forms, does it remain the same type of rock always? Possibly, but it most likely will not. Heat and pressure can change an igneous rock into a metamorphic rock. A metamorphic rock can be changed into another metamorphic rock or melted to form an igneous rock. Alternately, the metamorphic rock can be weathered and eroded into sediments that might become cemented into a sedimentary rock. In fact, any rock can be changed into any other type of rock. The continuous changing and remaking of rocks is called the **rock cycle.** The rock cycle is summarized in **Figure 23.** The arrows represent the different processes that change rocks into different types.

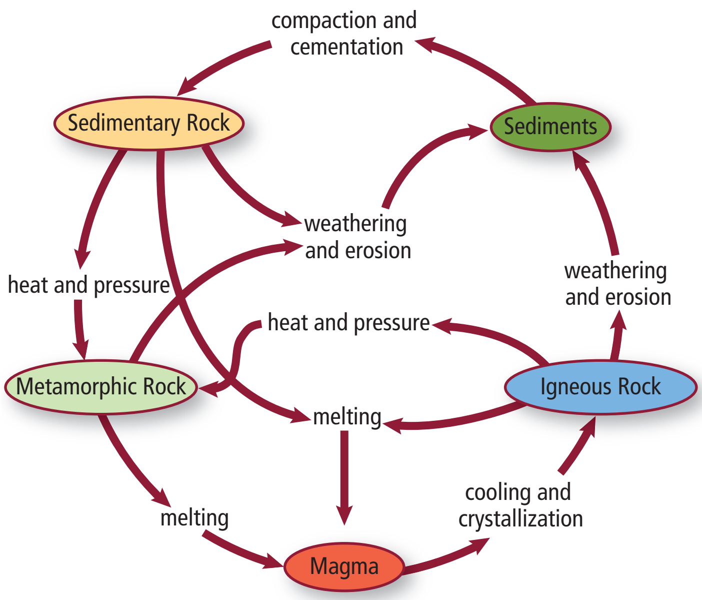


Figure 23 Rocks are continually being changed above and beneath Earth's surface. The rock cycle shows some of the series of changes rocks undergo.

SECTION 3 REVIEW

Section Self-Check

Section Summary

- The three main types of metamorphism are regional, contact, and hydrothermal.
- The texture of metamorphic rocks can be foliated or nonfoliated.
- During metamorphism, new minerals form that are stable under the increased temperature and pressure conditions.
- The rock cycle is the set of processes through which rocks continuously change into other types of rocks.

Understand Main Ideas

1. MAINIDEA **Summarize** how temperature increases can cause metamorphism.
2. **Summarize** what causes foliated metamorphic textures to form.
3. **Apply** the concept of the rock cycle to explain how the three main types of rocks are classified.
4. **Compare and contrast** the factors that cause the three main types of metamorphism.

Think Critically

5. **Infer** which steps in the rock cycle are skipped when granite metamorphoses to gneiss.
6. **Predict** the location of an igneous intrusion based on the following mineral data. Muscovite and chlorite were collected in the northern portion of the area of study; garnet and staurolite were collected in the southern portion of the area.

MATH IN Earth Science

7. Gemstones often form as porphyroblasts. Gemstones are described in terms of carat weight. A carat is equal to 0.2 g or 200 mg. A large garnet discovered in New York in 1885 weighs 4.4 kg and is 15 cm in diameter. What is the carat weight of this gemstone?

eXpeditions!

ON SITE: GEOLOGY IN CENTRAL PARK

Some people travel to remote locations of the world to see different types of rock. However, examples of rocks often can easily be found in urban areas. Central Park in New York City is an excellent place to find examples of igneous, sedimentary, and metamorphic rock, both naturally occurring and used for sculptures, monuments, and bridges.

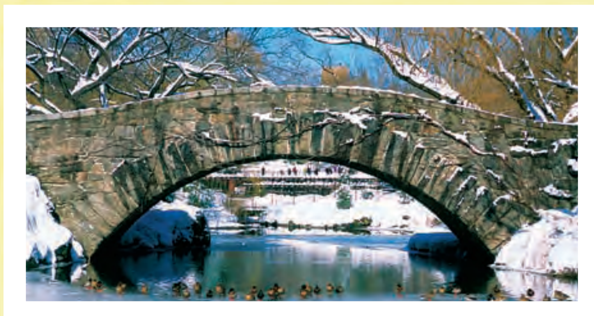
The Obelisk Weighing 221 tons and standing 21 m high, Cleopatra's Needle is the oldest human-made object in Central Park. The granite was quarried in Egypt more than 3000 years ago in 1475 B.C. The sculpture remained in Egypt until 1879, when it was moved to the United States. Granite is more resistant to weathering than other types of rock, and engravings made in granite can be read for hundreds of years, making it an excellent rock for the construction of monuments.

Cleopatra's Needle

Maine Monument

The Maine Monument Located at the main entrance to Central Park, the Maine Monument is an immense structure made of marble, limestone, and bronze. The massive bow of a ship that makes up the base of the monument was sculpted out of marble, a type of metamorphic rock. A bronze statue sits atop a 15-m limestone pylon.

Schist and gneiss These two types of metamorphic rock occur naturally in Central Park. Outcroppings of these rocks, formed from sedimentary or igneous rock under intense heat and pressure, can be found throughout the park. The Gapstow Bridge was constructed using the local bedrock.



Gapstow Bridge

(t)Rob Kim/Landov, (bl)Index Stock/Alamy Images, (br)Sandra Baker/Alamy Images, (bkgd)fStop/Getty Images

WRITING IN ▶ Earth Science

Promotional Brochure Research more information about the type of rock used to build structures and that occur naturally in your area. Create a promotional brochure that describes a tour focused on local geology.

WebQuest

GeoLAB

iLab Station

Interpret Changes In Rocks




Background: As the rock cycle continues and rocks change from one type to another, more changes occur than meet the eye. Color, grain size, texture, and mineral composition are easily observed and described visually. Yet, with mineral changes come changes in crystal structure and density. How can these be accounted for and described? Studying pairs of rocks can show you how.

Question: *How do the characteristics of sedimentary or igneous rocks compare to metamorphic rocks?*

Materials

samples of sandstone, shale, limestone, granite, quartzite, slate, marble, and gneiss
magnifying lens
paper
beam balance
100-mL graduated cylinder or beaker that is large enough to hold the rock samples
water

Safety Precautions

Procedure

1. Read and complete the lab safety form.
2. Prepare a data table similar to the one at the right. Adjust the width of the columns as needed.
3. Observe each rock sample. Record your observations in the data table.
4. Recall that density = mass/volume. Make a plan that will allow you to measure the mass and volume of a rock sample.
5. Determine the density of each rock sample, and record this information in the data table.

Sample Data Table

Sample Number	1	2	3	4
Rock type				
Specific characteristics				
Mass				
Volume				
Density				

Analyze and Conclude

1. **Compare and contrast** sandstone and quartzite.
2. **Describe** how the grain size of sandstone changes during metamorphism.
3. **Describe** the textural differences you observe between shale and slate.
4. **Infer** Compare your calculated densities to those calculated by other students. Infer why yours might differ.
5. **Explain** why the color of a sedimentary rock may change during metamorphism.
6. **Evaluate** the changes in density between shale and slate, sandstone and quartzite, limestone and marble, and granite and gneiss. Does density always change? Explain your results.

SHARE YOUR DATA

Peer Review Discuss your results with other groups in your class. Speculate on the reasons for variations in mass, volume, and density.

Matt Meadows

CHAPTER 6 STUDY GUIDE

BIGIDEA **Most rocks are formed from preexisting rocks through external and internal geologic processes.**

Vocabulary Practice

SECTION 1 Formation of Sedimentary Rocks

VOCABULARY
- sediment
- lithification
- cementation
- bedding
- graded bedding
- cross-bedding

MAINIDEA **Sediments produced by weathering and erosion form sedimentary rocks through the process of lithification.**

- The processes of weathering, erosion, deposition, and lithification form sedimentary rocks.
- Sediments are lithified into rock by the processes of compaction and cementation.
- Fossils are the remains or other evidence of once-living organisms that are often preserved in sedimentary rocks.
- Sedimentary rocks might contain features such as horizontal bedding, cross-bedding, and ripple marks.

SECTION 2 Types of Sedimentary Rocks

VOCABULARY
- clastic sedimentary rock
- clastic
- porosity
- evaporite

MAINIDEA **Sedimentary rocks are classified by their mode of formation.**

- Sedimentary rocks can be clastic, chemical, or biochemical.
- Clastic rocks form from sediments and are classified by particle size and shape.
- Chemical rocks form primarily from minerals precipitated from water.
- Biochemical rocks form from the remains of once-living organisms.
- Sedimentary rocks provide geologists with information about surface conditions that existed in Earth's past.

SECTION 3 Metamorphic Rocks

VOCABULARY
- foliated
- nonfoliated
- regional metamorphism
- contact metamorphism
- hydrothermal metamorphism
- rock cycle

MAINIDEA **Metamorphic rocks form when preexisting rocks are exposed to increases in temperature and pressure and to hydrothermal solutions.**

- The three main types of metamorphism are regional, contact, and hydrothermal.
- The texture of metamorphic rocks can be foliated or nonfoliated.
- During metamorphism, new minerals form that are stable under the increased temperature and pressure conditions.
- The rock cycle is the set of processes through which rocks continuously change into other types of rocks.

Chapter Self-Check

VOCABULARY REVIEW

Complete the sentences below using vocabulary terms from the Study Guide.

1. Compaction and cementation of clastic sediments result in ________.
2. Sedimentary layers that are deposited on an angle are called ________.
3. Cooling and crystallization, igneous rocks, uplift, and weathering and erosion describe a path along the ________.
4. Hot fluids that come in contact with solid rock result in ________.

Replace the italicized word with the correct vocabulary term from the Study Guide.

5. *Cementation* occurs when sediment gets deposited as the energy of the water decreases.
6. *Foliated* rocks have square, blocky crystals.

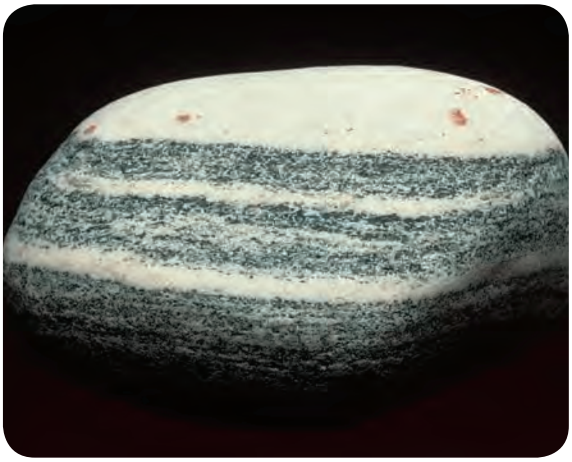
Write a sentence using each pair of words.

7. contact metamorphism, regional metamorphism
8. porosity, clastic sedimentary rock
9. sediment, bedding
10. clastic, evaporite

UNDERSTAND KEY CONCEPTS

11. Which clastic sediment has the smallest grain size?
    - **A.** sand
    - **B.** clay
    - **C.** pebbles
    - **D.** silt
12. Which is a coarse-grained clastic rock that contains angular fragments?
    - **A.** limestone
    - **B.** conglomerate
    - **C.** sandstone
    - **D.** breccia
13. Which is often a biochemical rock containing fossils?
    - **A.** chert
    - **B.** limestone
    - **C.** sandstone
    - **D.** breccia
14. Which process forms salt beds?
    - **A.** deposition
    - **B.** cementation
    - **C.** evaporation
    - **D.** lithification
15. Which does not cause metamorphism?
    - **A.** lithification
    - **B.** hydrothermal solutions
    - **C.** heat
    - **D.** pressure

Use the diagram below to answers Questions 16 and 17.



16. Which term best describes this rock's texture?
    - **A.** crystalline
    - **B.** nonfoliated
    - **C.** foliated
    - **D.** clastic
17. From what igneous rock does this sample usually form?
    - **A.** obsidian
    - **B.** basalt
    - **C.** granite
    - **D.** gabbro

18. Which agent of erosion can usually move only sand-sized or smaller particles?
    A. landslides
    B. glaciers
    C. water
    D. wind

19. Which would you expect to have the greatest porosity?
    A. sandstone
    B. gneiss
    C. shale
    D. quartzite

20. By what process are surface materials removed and transported from one location to another?
    A. weathering
    B. erosion
    C. deposition
    D. cementation

CONSTRUCTED RESPONSE

Use the diagram to answer Question 21.

21. **Describe** how the grains in the diagram become glued together.

22. **Summarize** the main difference between coquina and fossiliferous limestone. Use **Table 1** for help.

23. **Calculate** A sandstone block has a volume of 1 m^3 and a porosity of 30 percent. How many liters of water can this block hold?

24. **Illustrate** the conditions necessary to form a foliated metamorphic rock.

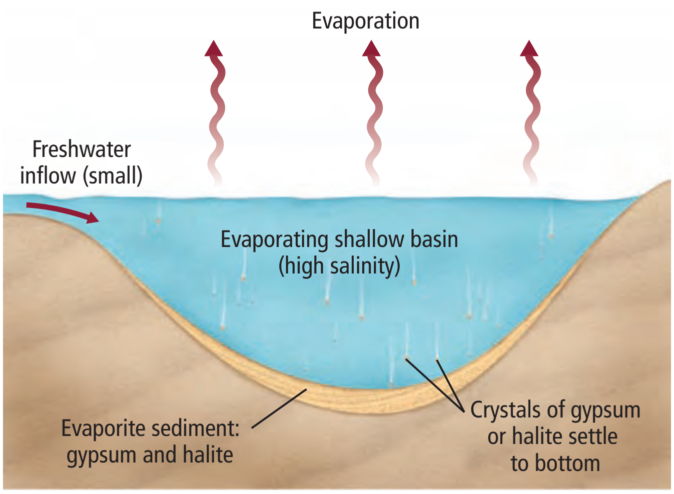
25. **Compare and contrast** the modes of lithification for sand and mud.

26. **Classify** the following types of sediments as either poorly sorted or well sorted: dune sand, landslide material, glacial deposits, and beach sand.

27. **Analyze** the effect that precipitation of calcite or iron oxide minerals has on clastic sediments.

28. **Compare and contrast** the character and formation of breccia and conglomerate.

Use the diagram below to answer Question 29.



29. **Evaluate** the effect that an opening to the ocean would have on this environment.

THINK CRITICALLY

30. **Incorporate** what you know about crystal form to explain why marble, even if formed under high pressure, does not show foliation.

31. **Compose** a statement to explain why the sedimentary rock coal does not meet the standard definition of a rock—an aggregate of minerals.

32. **Careers in Earth Science** Some sedimentologists work in sand and gravel pits where they analyze the material to best decide where and how it should be used. Infer why it is important for the sedimentologists to understand what would happen to the porosity of sand if finer-grained sediment were mixed in with the sand.

33. **Illustrate** an oil reservoir made up of layers of sandstone and shale. Indicate the position of the oil within the rocks.

34. **Assess** whether ripple marks and animal footprints preserved in sandstone are fossils. Explain your reasoning.

Use the figure below to answer Questions 35 and 36.

35. **Evaluate** the sediment in the layers in the figure. What type of bedding is this, and how well is it sorted? Explain.

36. **Infer** Look at **Figure 2** and explain which agents of erosion can produce the layers shown.

37. **Deduce** why glass on a quartz sand beach becomes rounded and frosted, while glass on a carbonate sand beach stays sharp and glassy.

CONCEPT MAPPING

38. Use the following terms to create a concept map that organizes sedimentary features: *ripple marks, graded bedding, horizontal bedding, asymmetrical, symmetrical, river current, wave action, wind deposited,* and *water deposited.* Some terms can be used more than once.

CHALLENGE QUESTION

39. **Hypothesize** At an approximate ocean depth of 4000 m, the carbonate compensation depth occurs. Below this depth, no calcium carbonate precipitates and no shells accumulate on the ocean floor. Hypothesize why this condition exists.

WRITING IN ▶ Earth Science

40. Imagine that you are planning a geologic walking tour of your community. Create a brochure highlighting the various natural building stones that are used in homes and buildings in your town or neighborhood.

DBQ Document–Based Questions

Data obtained from: Mineral Commodity Summaries. January 2006. *United States Geological Survey.*

Dimension stone is natural rock material used in construction, for monuments, and home interiors, such as kitchen countertops and floors. The principal rock types used are granite, limestone, marble, sandstone, and slate. Global resources of dimension stone are virtually limitless. Production of dimension stone in the United States and elsewhere has been steadily increasing.

Dimension Stone Production	U.S. Sold or Used (tonnage)	U.S. Sales or Uses (by value)
Limestone	39%	34%
Granite	29%	39%
Sandstone	14%	9%
Misc. stone	10%	7%
Marble	7%	6%
Slate	1%	5%

41. Construct a graph comparing the amount of dimension stone used by the value of the types of dimension stone.

42. Propose an explanation for why the value of granite is the highest of the dimension stones listed.

CUMULATIVE REVIEW

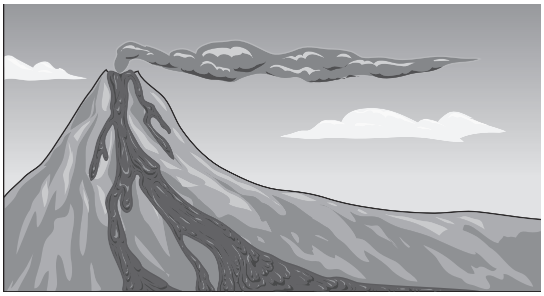
43. Compare and contrast the terms *science* and *technology.* **(Chapter 1)**

44. What is the formula of the ionic compound magnesium chloride? **(Chapter 3)**

45. Explain the concepts of partial melting and fractional crystallization. **(Chapter 5)**

MULTIPLE CHOICE

Use the illustration below to answer Questions 1 and 2.



1. Which rocks are most likely to metamorphose from the lava flow?
   A. only the rocks in the crater of the volcano, where the lava is hottest
   B. rocks in the crater and rocks along the top half of the mountain
   C. all the rocks on the mountain
   D. all the rocks reached by the lava flow

2. As the lava cools and crystallizes, what type of rock will form?
   A. sedimentary
   B. metamorphic
   C. extr usive igneous
   D. in trusive igneous

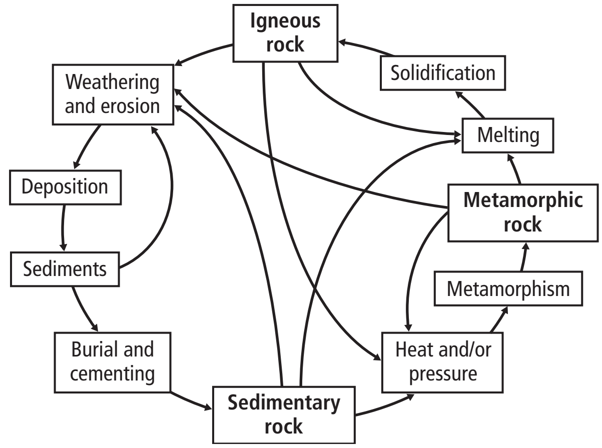
3. What is NaCl commonly known as?
   A. table salt C. water
   B. sugar D. natural chlorine

4. What initiates the process that changes sediments into sedimentary rocks?
   A. bedding C. cementation
   B. burial D. compaction

5. Identify the unit that is NOT accepted for use with Le Système International D'Unités (SI).
   A. metric ton C. ampere
   B. kilogram D. Fahrenheit

6. Which rocks are composed of minerals that form with blocky crystal shapes?
   A. foliated C. porphyroblasts
   B. nonfoliated D. gneiss

Use the diagram below to answer Questions 7 and 8.



7. Based on the diagram, which is the most reasonable hypothesis?
   A. Igneous rocks have layers caused by deposition.
   B. Sedimentary rocks contain grains of other rocks.
   C. Metamorphic rocks never have layers.
   D. Sedimentary rocks are always the same color.

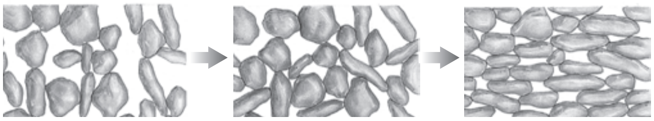
8. According to the rock cycle shown above, what most likely happens after the deposition of sediment?
   A. Weathering forms more sediment.
   B. Magma cools and forms igneous rock.
   C. Heat and pressure cause the sediment to melt.
   D. Cementation occurs and forms sedimentary rock.

9. Where are valence electrons located?
   A. every energy level
   B. middle energy levels
   C. the outermost energy level
   D. the innermost energy level

10. Which of the following is a fine-grained, clastic sedimentary rock?
   A. sha le
   B. sa ndstone
   C. pho sphate
   D. limest one

SHORT ANSWER

Use the illustration below to answer Questions 11 and 12.



11. What do you notice about the formation of sedimentary rock above?

12. Does this process represent compaction or cementation? Describe the difference between the two.

13. The results of an experiment show that as temperature increases, enzyme activity decreases. Describe what a line graph made from this data would look like.

14. Define *luster.* Why is it difficult to use luster to identify minerals?

15. What process does Bowen's reaction series illustrate?

16. Boron has an atomic number of 5. Describe an atom of boron with a mass number of 10 and an atom of boron with a mass number of 11 in terms of their atomic particles. What is unique about these two atoms of boron?

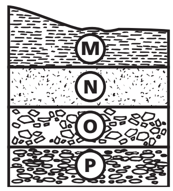
17. Briefly describe the process by which magma becomes igneous rock.

18. How does studying sedimentary rock layers and understanding how they form help paleontologists learn about Earth's history?

READING FOR COMPREHENSION

Sedimentary Rock Layers

Paleontologists wanted to study the sedimentary rock layers and their contents of a particular area. The diagram shows a cross section of the rock layers they studied. The table shows the data the scientists were able to collect.



Age of Sedimentary Rock Layers

Layer	Composition	Estimated Age (years)	Depth (meters)
M	sedimentary rock	100,000	0–4
N	sedimentary rock	Unknown	5–7
O	sedimentary rock	6 million	8–9
P	sedimentary rock	6.1 million	9–10

19. What could the paleontologists have recorded to improve their study?
    - **A.** time of year
    - **B.** age of layer N
    - **C.** location of the work site
    - **D.** mass of the sedimentary rocks

20. If fossils of a species were found in Layers O and P, but not M and N, which could you conclude?
    - **A.** The species does not exist anywhere on Earth today.
    - **B.** The species evolved into a completely different species.
    - **C.** The species became extinct less than 100,000 years ago.
    - **D.** The species disappeared from the area around 6 mya.

NEED EXTRA HELP?

If You Missed Question . . .	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Review Section . . .	6.3	5.1	3.2	6.1	1.2	6.3	6.3	6.3	3.1	6.2	6.1	6.1	1.3	4.1	5.1	3.1	5.1	6.1