Earth Materials—Minerals, Rocks, and Mineral Resources

TOPIC 11

How Scientists Study Minerals

Do you think every mineral has a unique chemical composition?

It is the crystal structure that is unique to each mineral and not the chemical composition. Just consider the minerals graphite and diamond, which are both composed of only carbon. It is hard to believe that two minerals with the same chemical composition could be so different: Graphite is one of the softest minerals and diamond is the hardest of the somewhat common minerals. Diamond has a brilliant luster and graphite is greasy to metallic. Graphite is used as a lubricant, while diamond is used as an abrasive. And graphite is an electrical conductor, while diamond is an insulator.

Graphite and diamond are not the only example. Calcite and aragonite are two minerals that are composed of calcium carbonate ($CaCO_3$). There are at least five minerals with the formula SiO_2, with quartz being the most common.

TOPIC 11

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Vocabulary

bioclastic sedimentary rocks
chemical sedimentary rocks
clastic sedimentary rock
cleavage
contact metamorphism
crystal shape
crystal structure
extrusive igneous rock
foliation
fossil
fracture
hardness
igneous rock
inorganic
intrusive igneous rock
luster
magma
metamorphic rocks
metamorphism
mineral
mineral crystal
mineral resources
organic
precipitation (of minerals)
regional metamorphism
rock cycle
sedimentary rocks
streak
texture

Topic Overview

Rocks and minerals are the source of much of the material and energy that people want or need. If you make a list of about one hundred objects you used or wanted to use today, most likely 95 to 100 percent of them come from rocks and minerals. Earth materials—minerals, rocks, and mineral resources—are of value to people in many ways. Earth materials fuel our industrial society as extracted fossil fuels. They provide the raw materials for the building of homes and other construction projects. Rocks and minerals make up Earth's solid surface—the lithosphere—that you live on. When Earth's solid surface is weathered and eroded, the end results are the landscape features that people live, work, and play on.

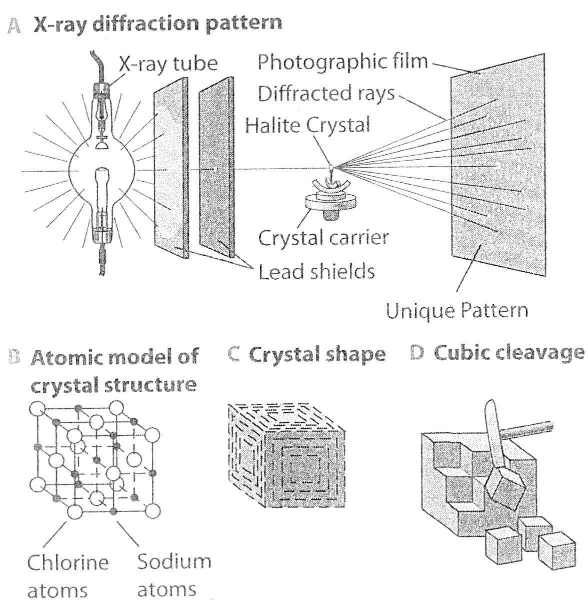


Figure 11-1. Crystal structure and properties of the mineral halite: Halite is the mineral with the formula NaCl (sodium chloride). It is the one mineral of rock salt and common table salt.

Minerals

Minerals have characteristic physical and chemical properties. Some of these properties are color, streak, luster, hardness, density, cleavage and crystal structure.

What a Mineral Is

A **mineral** is a naturally occurring, inorganic, crystalline solid having a definite chemical composition. A mineral is considered to be naturally occurring because it is formed in nature and not made by people. It is **inorganic** because it has not been made by or composed of life forms. Thus fossil fuels or a pearl from an oyster are NOT minerals.

A mineral is crystalline because its atoms have a specific arrangement. This arrangement of atoms is called **crystal structure**. Each mineral has its own distinctive crystal structure that can lead to very accurate identifications through the use of X-rays. Figure 11-1 illustrates the crystal structure of a mineral.

All minerals are solids that are composed of one or more chemical elements. The chemical composition of a mineral describes the types and ratios of elements that make up the mineral. Some minerals contain only one element and others are compounds of two or more elements. You can find the characteristics of some minerals in the Properties of Common Minerals in the *Earth Science Reference Tables*.

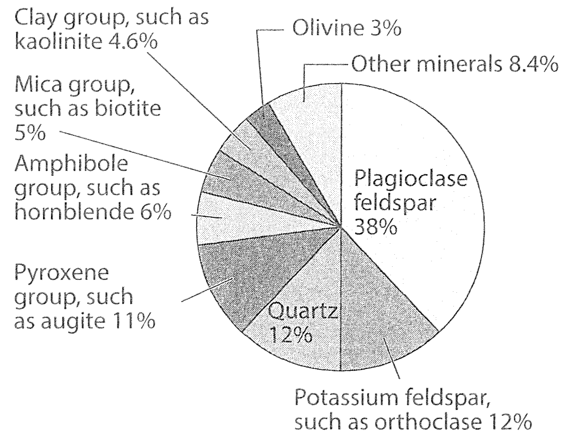
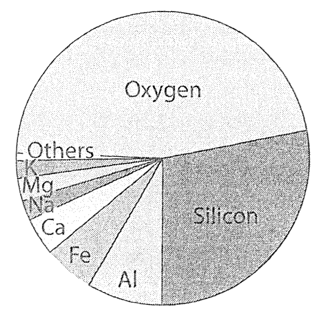


Figure 11-2. Circle graph of the most common minerals of Earth's crust: 90 percent of Earth's crust by weight is composed of eight minerals or groups of minerals—all silicates. These common minerals are called rock-forming minerals.

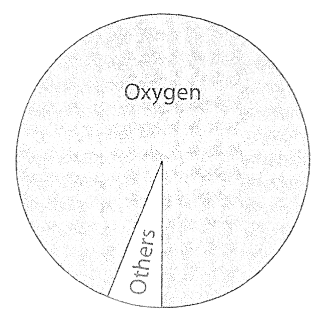
Relation of Minerals to Rocks

All minerals are rocks, but not all rocks are minerals nor are they all composed of minerals. A rock is any naturally formed solid that is part of Earth or any other celestial body. Though a large percentage of rocks is composed of minerals, many rocks are composed of organic or glassy materials that are not minerals. Glasses are not minerals because their atoms are not arranged in a specific pattern. The majority of rocks are made of two or more minerals—multiple-mineral rocks. Some rocks are composed of only one mineral—single-mineral rocks.

A review of the three schemes for rock identification—sedimentary, metamorphic, and igneous—in the *Earth Science Reference Tables* and Figure 11-2 indicates that only a small number of minerals are commonly found in rocks. These 20 to 30 very common minerals, found in rocks, are called the rock-forming minerals. Many of these rock-forming minerals are listed in the Properties of Common Minerals in the *Earth Science Reference Tables.*



Relative amounts by mass



Relative amounts by volume

Figure 11-3. Percentages of the chief elements in Earth's crust by mass and by volume: Volume is the amount of space occupied by the atoms of each element in the solid substances of the crust. Also see Average Chemical Composition of Earth's Crust, Hydrosphere, and Troposphere in the *Earth Science Reference Tables.*

Element Composition of Earth's Crust

The chemical element composition of Earth's crust is shown in Figure 11-3.

- The graph indicates that over 99 percent of Earth's crust and its minerals are, by volume and mass, composed of only 8 of the 90 naturally occurring elements found on Earth.
- Silicon is the second most abundant element by mass, but the element potassium is number two in crustal abundance by volume because of its lower density and higher volume.

Mineral Crystal Structure

The crystal structure, or atomic arrangement of the atoms, that comprise minerals is responsible for many of their chemical and physical properties, such as crystal form, breaking pattern, and hardness. Most rock-forming minerals are silicates. Silicate minerals have a structure that results from various arrangements of a tetrahedron-shaped (4-sided) unit of oxygen and silicon called the silicon-oxygen tetrahedron. Figure 11-4 shows how each tetrahedron is composed of one atom of silicon and four atoms of oxygen. It also shows different ways the silicon-oxygen tetrahedron can be arranged resulting in different breaking patterns (cleavage and fracture).

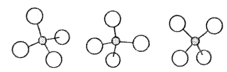
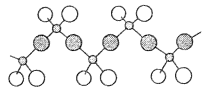
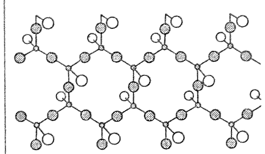
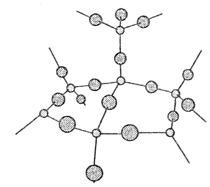
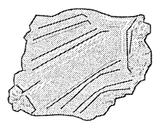
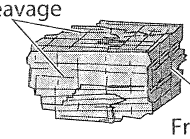
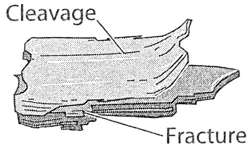
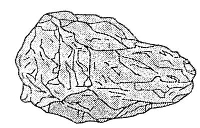
Silicate structure	Key ⌖ Silicon ● Shared oxygen ○ Unshared oxygen 			
Silicate structure	Single tetrahedron	Chains of tetrahedra	Sheets of tetrahedra	A network of tetrahedra in three dimensions
Mineral example	Olivine—peridot is gem variety	Pyroxene, such as augite	Mica, such as biotite	Quartz
Cleavage or fracture type	Curved or conchoidal fracture	Two directions of cleavage into blocky or splinter shapes and fracture	One direction of cleavage into sheets and fracture	Curved or conchoidal fracture
Drawing				

Figure 11-4. Various arrangements of the silicon-oxygen tetrahedron in silicate minerals: The tetrahedra combine with themselves and other elements in different atomic structures. The different combinations affect the physical properties of the minerals—including cleavage and fracture patterns shown in the illustration.

Digging Deeper

Diamond is still the hardest mineral that a person is likely to encounter, but not the hardest in the world. Scientists have recently discovered that wurtzite boron nitride and lonsdaleite, two very rare minerals, are even harder than diamond.

Mineral Formation

Since all minerals are rocks, they form by one of two processes. Minerals form as the result of inorganic crystallization—a process of organizing atoms to form crystalline solids. Minerals also form by recrystallization of atoms from the solids, liquids, and gases associated with various rock- forming environments.

Mineral Properties and Identification

Each mineral has a characteristic set of physical and chemical properties that can be used to help identify it. The crystal structure and the chemical composition of minerals largely determine these properties. Some properties, such as color, are often caused by impurities. The mineral corundum, when pure, is colorless. However, with slight chemical impurities, corundum becomes the blue sapphire or red ruby.

The most accurate method for identifying minerals is by the use of X-ray diffraction instruments (see Figure 11-1) and other machines not available to most individuals. Therefore, simple tests and mineral identification charts are relied on. An example of a mineral identification key, or chart, (R) is found in Properties of Common Minerals in the *Earth Science Reference Tables*.

Color The color of a mineral is one of its most obvious properties. However, in most cases color is not useful because many minerals have the same color. In addition, the color of many minerals varies due to impurities, and many minerals are clear or colorless when pure. In a few cases however, such as in the yellow of sulfur, the gray of graphite (pencil lead) and galena, or the brassy yellow of pyrite (fool's gold), the mineral's color is usually consistent.

Streak The color of finely crushed residue or powder of a mineral is its **streak**. When you write on a chalkboard, you observe the streak of the rock chalk. The streak of a mineral is usually quite consistent; thus streak color is much more useful than mineral color. For example, the iron ore mineral, hematite, can be various shades of silver-gray to red in color, but the streak is a consistent red.

Luster The shine from an unweathered mineral's surface, or the way a mineral looks in reflected light, is **luster**. There are two broad groups of luster—metallic and nonmetallic. Minerals with a metallic luster, such as pyrite and galena, shine like the surface of a clean stainless steel pot. Most minerals have a nonmetallic luster. There are many types of nonmetallic luster, such as the glassy luster of black hornblende and clear quartz "rhinestone," or the pearly luster of muscovite mica.

Hardness The resistance a mineral offers to being scratched is its **hardness**—the scratchability of a mineral, not how easily the mineral breaks. Diamond is the hardest mineral (see Digging Deeper on page 220), but drop an unmounted diamond on a tile floor and it will likely shatter. On the other hand, if the very soft mineral graphite is dropped, only a small amount will chip off, or cleave.

Figure 11-5 shows the Mohs hardness scale and some other common materials that are often used to determine hardness. Mohs hardness scale is arranged from the softest #1 (talc) to the hardest #10 (diamond). A quick way to determine relative hardness is to use a piece of window glass. If a mineral scratches the glass, the mineral is hard, and if it doesn't, it is soft.

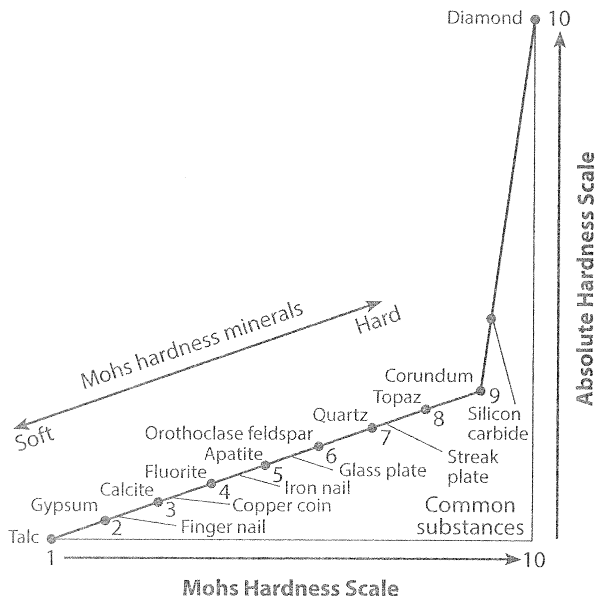


Figure 11-5. Mohs and absolute hardness scale: The differences in the hardnesses on the Mohs scale vary, as shown by the comparison to an absolute scale of hardness. Note that on the absolute scale, the difference of hardness between diamond and corundum—ruby or sapphire—is more than all the way from talc to corundum.

Density Each mineral has a specific density or a small range of densities—for those minerals that vary in mineral composition. Often in mineral studies, density is stated as specific gravity, a value without units. Specific gravity is the density of a mineral compared to the density of water. Specific gravity is a good test to distinguish gemstones, because it doesn't harm the samples like hardness or cleavage tests do. In mining and refining processes, differences in the densities of various minerals allow them to be separated. A common example is the panning of high-density gold.

Cleavage The tendency of a mineral to break along the zones of weakness and form smooth to semi-smooth parallel sides, or surfaces, is called **cleavage**. Cleavage surfaces can often be distinguished from sides without cleavage by having a shinier or more brilliant luster (smooth surfaces reflect better). If a mineral lacks preferred zones of weakness in the crystal structure, then it will demonstrate uneven breaking surfaces called **fracture**. For example, some types of fracture are irregular (earthy), fibrous (splintery), and curved (conchoidal). The curved surfaces in a type of quartz called flint make this

MemoryJogger

Recall that density is the ratio of the mass of an object to its volume. Therefore, an element that has a lower density than another element has a smaller mass per volume than an element with higher density.

material very useful in making knives and arrowheads. Often a mineral will have both cleavage and fracture on different sides, such as the silicates hornblende and the feldspars. (See Figures 11-4 and 11-6)

Crystal Structure The outward geometric shape of a mineral, the crystal form, or **crystal shape,** reflects the crystal structure—orderly arrangement of the atoms in the mineral. It is only when individual mineral grains have the room to freely grow that this crystal shape, with its smooth sides or faces, can take shape. This is the reason most mineral samples found in nature don't illustrate the crystal forms; the use of crystal form in mineral identification is limited. Another problem is that even though the internal crystal structure of minerals is unique, the outward crystal shape, such as the cubic shape of halite, galena, and fluorite, isn't unique. Also, any mineral can have many different crystal shapes.

Other Mineral Properties Besides physical properties, some chemical properties of minerals are also used for identification. One of these chemical properties is the reaction of a mineral with acid. When a small amount of dilute hydrochloric acid is placed on a mineral or rock containing calcite (CaCO3), the mineral or rock will bubble (effervesce)—giving off carbon dioxide. The mineral dolomite can be distinguished from calcite, because dolomite will bubble in acid only after the mineral is powdered.

Many other chemical and physical properties are used to identify minerals. Many of the properties only apply to a few minerals and will often be the key to a mineral's identification. For example, some minerals such as thin pieces of muscovite and biotite micas are flexible. This means that they can be bent and will snap back to their original shape. Other properties used for identification are found in Properties of Common Minerals in the *Earth Science Reference Tables.* Ⓡ

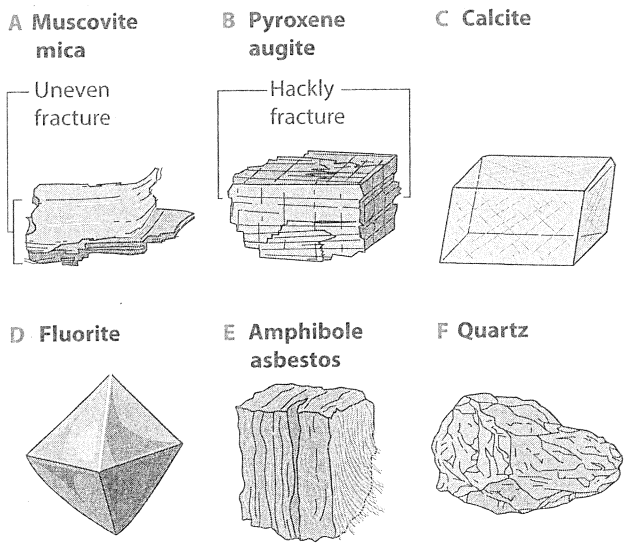


Figure 11-6. Types of cleavage and fracture: (A) shows one direction of cleavage and some uneven fracture. (B) shows two directions of cleavage and a hackly (bumpy) fracture. (C) shows three directions of cleavage. (D) shows four directions of cleavage. (E) shows fibrous fracture. (F) shows curved fracture.

Digging Deeper

A few minerals have very fine lines—called striations—on cleavage surfaces and on the faces of their crystal form. These striations can be used to distinguish the mineral plagioclase feldspar from the potassium feldspars such as orthoclase. Striations are an outward expression of the internal arrangement of the atoms within a mineral.

Review Questions

1. A mineral CANNOT be
   (1) organic
   (2) crystalline
   (3) a solid
   (4) formed in nature

2. Which rock is usually composed of several different minerals?
   (1) rock gypsum
   (2) limestone
   (3) quartzite
   (4) gneiss

3. Only a small number of Earth's minerals are commonly found in rocks. This fact indicates that most
   (1) minerals weather before they can be identified
   (2) minerals have properties that are difficult to identify
   (3) rocks have a number of minerals in common
   (4) exposed surface rocks are mostly igneous

4. The data table shows the composition of six common rock-forming minerals.

Mineral	Composition
Muscovite Mica	$KAl_3Si_3O_{10}$
Olivine	$(FeMg)_2SiO_4$
Orthoclase	$KAlSi_3O_8$
Plagioclase	$NaAlSi_3O_8$
Pyroxene	$CaMgSi_2O_6$
Quartz	SiO_2

The data table provides evidence that

(1) the same elements are found in all minerals
(2) a few elements are found in many minerals
(3) all elements are found in only a few minerals
(4) all elements are found in all minerals

5. What are the four most abundant elements, by volume, in Earth's crust?

(1) oxygen, potassium, sodium, and calcium
(2) hydrogen, oxygen, nitrogen, and potassium
(3) aluminum, iron, silicon, and magnesium
(4) aluminum, calcium, hydrogen, and iron

6. Diamonds and graphite are both minerals that are composed of the element carbon. Diamond has a hardness of 10, while graphite has a hardness of 1. Based on your knowledge of earth science, what is the most probable cause of this difference in hardness?

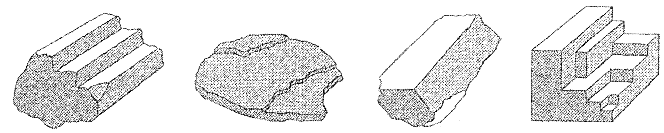
7. Minerals are composed of

(1) one or more rocks
(2) only one rock
(3) one or more chemical elements
(4) only one metal

8. The cubic shape of a mineral crystal is most likely the result of that crystal's

(1) hardness
(2) density distribution
(3) internal arrangement of atoms
(4) intensity of radioactive decay

9. The following diagrams represent four different mineral samples.



Which mineral property is best represented by the samples?

(1) density (3) hardness
(2) cleavage (4) streak

10. Minerals are identified on the basis of

(1) the method by which they were formed
(2) the type of rock in which they are found
(3) the size of their crystals
(4) their physical and chemical properties

11. A six-sided mineral crystal is a very hard mineral called

(1) hornblende (3) quartz
(2) orthoclase feldspar (4) biotite mica

12. The relative hardness of a mineral can best be tested by

(1) scratching the mineral across a glass plate
(2) squeezing the mineral with calibrated pliers
(3) determining the density of the mineral
(4) breaking the mineral with a hammer

13. What property would a mineral have if it appears like a new quarter in reflected light?

(1) a metallic luster
(2) metallic element composition
(3) magnetic
(4) a high density

14. Which property of the mineral diamond allows diamond powder to be used to shape gems for jewelry?

(1) crystal shape (3) luster
(2) cleavage (4) hardness

15. What information about a mineral is needed to determine its density?

(1) shape and volume
(2) shape and mass
(3) volume and mass
(4) volume and hardness

Rocks

A rock is any naturally formed solid on Earth or in any part of the universe. The definitions for rock and the individual rock types are not nearly as specific as those for a mineral. The reason is that rocks, except for the single-mineral ones, are mixtures of minerals, organic materials, glasses, and fragments of other rocks. A single-mineral rock is both a rock and a mineral and has a mineral's definite composition and properties.

In your study of rocks you will often have to refer to parts of the Ⓡ *Earth Science Reference Tables*. The Generalized Landscape Regions of New York State and the Generalized Bedrock Geology of New York State will allow you to see in which portions of New York State different rock types are found and the geologic ages (periods) of the rocks. The Rock Cycle in Earth's Crust diagram will allow you to quickly understand the relationships among the three major rock types and the processes that form them. The Scheme for Igneous Rock Identification, Scheme for Sedimentary Rock Identification, and Scheme for Metamorphic Rock Identification will provide you with the basic individual rock properties and how to identify most of the important rock types.

Rock Types

Rocks are classified into three categories—sedimentary, igneous, and metamorphic—based on the three methods of rock formation. Sometimes metamorphic and igneous rocks are grouped together as nonsedimentary rocks. As a group, rocks are distinguished and identified based on their composition and the texture. The **texture** of a rock is not how rough it feels, but the size, shape, and arrangement of the materials the rock is composed of. The majority of rocks are composed of individual grains of minerals called **mineral crystals.** Rocks that are made of intergrown or interconnecting mineral crystals are called crystalline.

Sedimentary Rocks

Rocks that form from an accumulation of sediments derived from preexisting rocks and/or organic materials are **sedimentary rocks**. These rocks form by various processes that occur on or within the top few kilometers of Earth's crust.

Formation of Sedimentary Rocks Most sedimentary rocks are made up of solid fragments or sediments, often called "clasts," that have been weathered or eroded from older rocks. After formation, erosional agents, such as running water, glaciers, wind, ocean waves, currents, and gravity transport sediments to new locations under water or on land. Most sedimentary rocks form under large bodies of water, such as lakes, seas, and oceans, where the sediments are usually deposited in horizontal layers. Some methods of formation of sedimentary rocks are cementation, compaction, chemical action, and organic processes.

Digging Deeper

Most precipitation of minerals occurs at the bottoms of lakes, seas, and oceans; but it also happens in soil, in caves—forming rock "icicles"— around mineral springs, and in homes—forming a rock film on water glasses and shower stalls.

Cementation Often the clasts, such as sand, silt, and pebbles, are cemented together in a process called cementation. This happens as the sediments lose water and the dissolved minerals in the pores of sediments precipitate out, forming crystalline mineral material. Minerals, such as calcite, quartz, and hematite, are the common cements that glue the solid sediments together. Cementation can happen alone or in combination with other processes to form the clastic sedimentary rocks, such as siltstone and conglomerate. A **clastic sedimentary rock** is one that is largely composed of solid sediments, such as the sand in sandstone, or the tiny pieces of clay in shale.

Compaction Crustal movements and the weight of overlying water and sediments compress, or compact, sediments. This causes a reduction in volume due to the loss of pore space and water. The process is called compaction. While some sedimentary rocks, such as shale and bituminous coal, may form only by compaction, most of the clastic or fragmental rocks form due to compaction and cementation.

Chemical Action All natural liquid water on Earth contains dissolved minerals. In water, these dissolved minerals are called by various names—hardness in drinking water and salts in the sea—but they are all minerals that have been dissolved by chemical weathering. When these dissolved minerals precipitate, or drop out from the water, they often form a crystalline mass of intergrown or interconnected mineral crystals called a **chemical sedimentary rock or evaporites**. This **precipitation** of minerals is the result of evaporation, saturation with dissolved minerals, or changes in temperature. Chemical sedimentary rocks or evaporites, are composed of interconnected crystals of just one mineral.

Organic Processes When dissolved minerals are withdrawn from water by life forms, it is termed chemical—not mineral—precipitation. **Organic** means anything related to living organisms or to things that were alive. Any rock made by living organisms or mostly composed of materials from life forms is an organic, or **bioclastic sedimentary rock.** When a clam makes a shell, a coral makes a skeleton, or you make bones and teeth, chemicals are precipitated from water. Some organic sedimentary rocks, such as the limestone of a coral reef, are formed directly by chemical precipitation.

Characteristics of Sedimentary Rocks Some features that distinguish sedimentary rocks from igneous and metamorphic rocks include the following:

- Most sedimentary rocks are clastic—composed of fragments called sediments, or clasts.
- The clasts or sediments are usually rounded particles because they have been moved by running water, wind, waves, or ocean currents.
- The clasts or sediments are often sorted into a small range of sizes because of horizontal sorting.
- Some sedimentary rocks are organic and thus contain fossils. A **fossil** is any evidence of former life.
- One of the most distinguishing characteristics of sedimentary rocks is the beds or strata—parallel layers of the sediments in the rock. These beds are often seen in hand specimens, but are even more obvious outside where sedimentary rocks are exposed at Earth's surface in places such as road cuts or stream valleys.
- Sedimentary rocks often contain features that indicate they formed at Earth's solid surface. Some features might be mud cracks, rain drop impressions, or ripple marks that formed on the top of a sand dune or at the bottom of the ocean. Other features might be fossils that indicate an earlier Earth's surface.
- The chemical sedimentary rocks are not composed of sediments or clasts, but are composed of interconnected mineral crystals of one mineral variety.

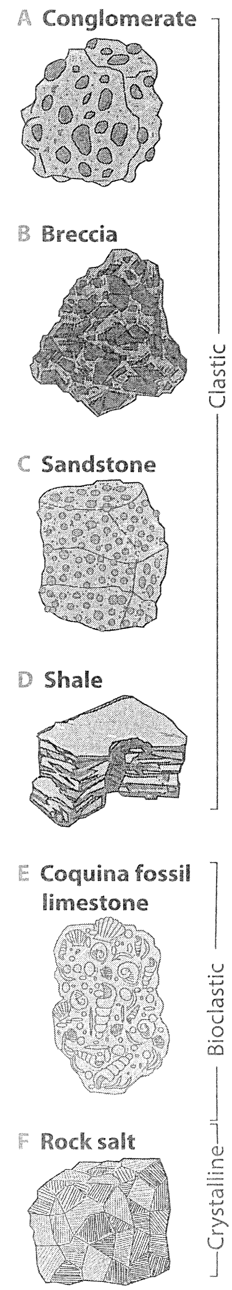


Figure 11-7. Some characteristics of sedimentary rocks: In diagrams A, B, and C the dark shading is sediment and the light color is the cement. (A) has unsorted sediments, mostly larger than sand, cemented together. (B) has sediments similar to conglomerate that are angular, not rounded. (C) has sorted sand-size sediments cemented together. (D) has compacted and sometimes cemented clay-sized sediments. (E) is an organic rock composed of shells cemented together. (F) is a chemical sedimentary rock of intergrown mineral crystals of the mineral halite.

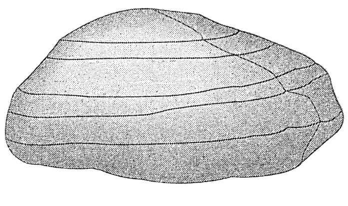


Figure 11-8. Layers in a sedimentary rock: Layers—called beds or strata—result from changes, often minor, in the types of sediment deposited at different times.

Identifying Sedimentary Rocks The more common clastic, or fragmental, sedimentary rocks are distinguished largely on the basis of their sediments—clay, silt, sand, or larger sediment sizes. If the sediments of a conglomerate are mostly rounded, the rock is regular conglomerate. If the sediments are mostly angular the rock is breccia. In basic rock identification, it makes no difference what type of mineral or rock fragments are in a clastic rock—texture is the main factor used for classification and identification. For example, if a rock is composed of sand-sized sediments, the rock is sandstone. Refer to the chart Scheme for Sedimentary Rock Identification in the *Earth Science Reference Tables.* (R)

This chart also shows that nonclastic rocks are predominantly composed of one mineral. Therefore, you treat most of them as if they are minerals. Bioclastic limestone is composed of $CaCO_3$, so it will easily fizz in dilute hydrochloric acid. If the rock only fizzes after some of it is powdered, then the rock is likely dolostone. Other examples of nonclastic rocks are rock salt, composed of the mineral halite, and rock gypsum, composed of the mineral gypsum.

Digging Deeper

To measure sand or larger sediments in a rock, a ruler can be placed on or next to the rock. If you can't easily see the sediments, but the rock feels gritty to a fingernail, then it is most likely siltstone. You can use a magnifying glass or microscope to see silt-sized sediments. If you can't see the sediments under a normal microscope, or if the rock does not feel gritty, it is likely shale.

Igneous Rocks

Rocks that form when natural, molten (liquid) rock-forming material cools and turns into a solid are **igneous rocks.** Liquid rock material beneath Earth's solid surface is called **magma.** When magma comes out onto or above Earth's solid surface, it becomes lava. If Earth was largely molten in its earliest stages of formation, then igneous rocks were the first rocks to form on Earth.

When magma solidifies beneath Earth's solid surface, it forms rocks called **intrusive** (plutonic) **igneous rocks.** The bodies, or masses, of these rocks can range from finger size up to the size of one or more of our states, such as Vermont. These bodies are called intrusions. Figure 11-9 illustrates many of the types of intrusions from the thin dikes and sills, common as light and

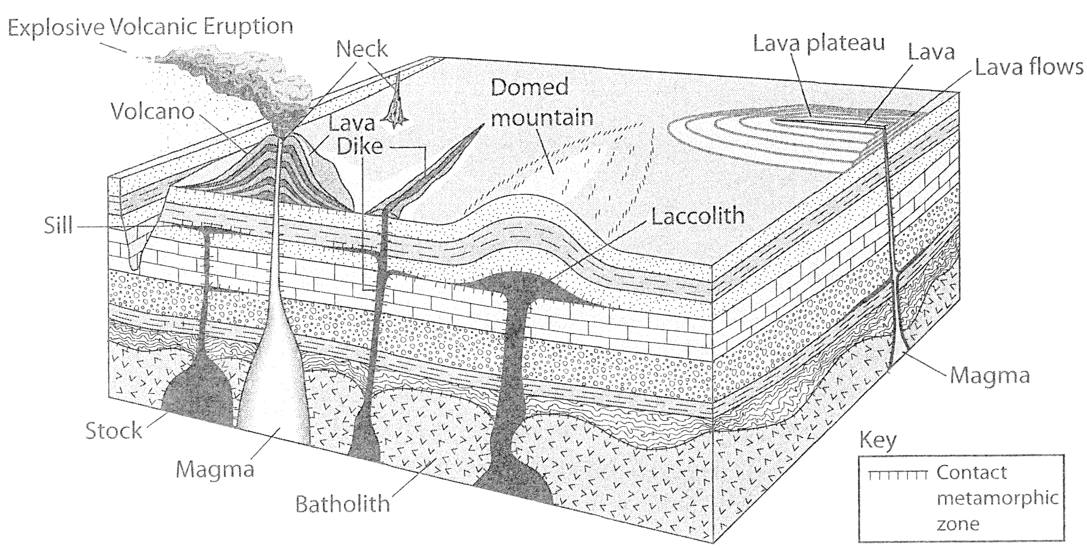


Figure 11-9. Examples of igneous intrusions and extrusions: The types of intrusions are batholith, stock, laccolith, sill, and dike. (Except for sill, you need not know the names of the various types of intrusions.) Note that both the volcano and the laccolith intrusion have formed mountains.

dark streaks in eastern New York State road cuts, to massive batholiths. It is believed that most intrusions form, within Earth's solid outer layer—the lithosphere.

When lava solidifies on or above Earth's solid surface, the result is **extrusive igneous rock.** Extrusive, or volcanic rocks, form landscape features called extrusions. The two most common extrusions are lava flows and volcanoes. (See Figure 11-9.)

Formation of Igneous Rocks All igneous rocks are the result of solidification—the change from a liquid to a solid. Most igneous rocks are produced as a result of the type of solidification called crystallization. Crystallization results when molten lava or magma cools and forms a solid composed of intergrown mineral crystals—a crystalline rock. Some igneous rocks that form at or above Earth's surface cool so fast that mineral crystals don't have a chance to form. The result is a type of solid called glass. In glass there is no pattern or arrangement of the atoms, therefore the substance is non-crystalline.

Crystal Sizes and Glasses The size of the crystals in an igneous rock depends on the conditions in which the rock formed. The immediate cause of the difference in the size of the crystals, or lack of crystals, is the time in which the cooling takes place. Generally, the longer the time of cooling, the larger the crystals become. However, the cooling time itself depends on the temperature and pressure of the environment, and the composition of the magma or lava. Generally, molten rock low in silica (SiO_2) content or high in water content will take longer to cool. The pressure and temperature deep within the lithosphere are very high, and therefore magma cools slowly—over many thousands of years. The result is rocks with large or coarse crystals easily visible to the human eye.

The temperature and pressure at or near Earth's surface are much lower, and the lava there cools much more quickly, forming fine-grained rocks with small crystals, not easily seen with the unaided human eye. If the cooling is very fast (usually seconds to hours), a glassy rock with no or few mineral crystals forms. Most lava flows and volcanoes are composed of rocks with small mineral crystals or no crystals in them.

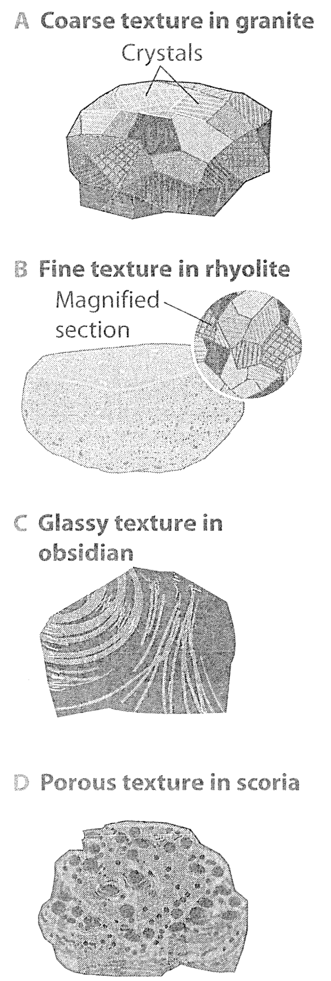


Figure 11-10. Textures of igneous rocks: (A) Slow cooling of magma results in coarse-sized crystals easily visible to the unaided eye. (B) Fast cooling of lava at Earth's surface results in fine-sized crystals not easily visible without magnification. A magnified section resembles the texture in (A). (C) If lava cools very rapidly, a rock with a glassy texture of no minerals will form. (D) In fine—or glassy—textured rocks or extrusive igneous rocks, there is often a mixed, porous vesicular texture. The pores are due to expanding gas forming bubbles in the lava as it solidified.

Textures of Igneous Rocks Texture in igneous rocks depends on the size of mineral crystals, the presence of glass and rounded pores (vesicles). These features are related to the cooling time of magma or lava and the rock-forming environment. (See Figure 11-10). Rocks with crystals easily seen by the unaided eye are coarse-textured intrusive rocks like granite and gabbro, and almost always form within the lithosphere. Medium textured rocks like diabase have barely visible crystals. Pegmatite intrusive rocks have a very coarse texture and can have meter sized crystals.

Associated with lava flows and volcanoes, most of the extrusive igneous rocks have a fine texture of crystals smaller than one millimeter in size. To clearly see mineral crystals in fine-textured rocks, such as basalt and rhyolite, magnification is required. Many of the extrusive igneous rocks of lava flows and volcanoes have rounded openings in them caused by lava solidifying around trapped expanding gases. The rocks with these openings are said to have a vesicular texture. These openings or pockets are like the pores in the foam produced when you shake up a carbonated

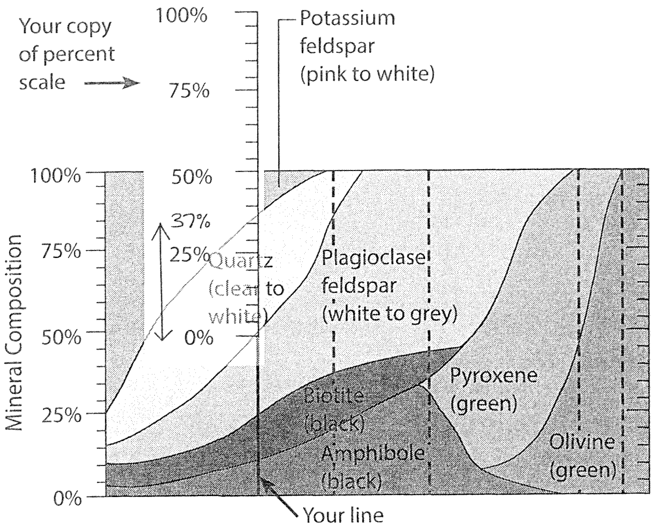


Figure 11-11. How to use the Scheme for Igneous Rock Identification in the *Earth Science Reference Tables* to measure the percent of mineral composition: Refer to the identification scheme in the *Earth Science Reference Tables* as you proceed. To obtain a percent for a particular part of the chart, do the following: (1) Copy the scale from the left side of the chart. (2) Draw a vertical line on the chart in pencil through the "t" in the word "quartz," as shown. (3) To compute the mineral composition of quartz, place your copy of the percent scale on the chart along your drawn line, as shown. (4) Align the 0% of your copy of the scale with the bottom of the quartz portion of the chart and read the percent at the top part of the mineral. The art shows quartz at about 37%. (5) Repeat this procedure for each of the other minerals. The values for the other minerals are: amphibole 10%, biotite 13%, plagioclase feldspar 24%, and potassium feldspar 14%. Usually you can obtain answers within 2–3 percent of the actual value.

soft drink. Basalt with many pores is called vesicular basalt. Volcanic glass with many pores is called pumice or scoria depending upon color and composition. In pumice the vesticular texture is often due to gases expanding in lava during an explosive volcanic eruption.

Identification of Igneous Rocks Igneous rocks are identified largely on the basis of texture (very coarse, coarse, medium, fine, glassy, or vesicular) and percent mineral composition. In the coarse-grained rocks you can often identify the minerals easily because they are visible to the unaided eye. You match the percents of what you observe in the rock with the chart of percent by volume of the surface of a rock. With a strong enough microscope the same thing can be done with the fine-textured rocks. For aid in using the percent mineral composition chart see Figure 11-11.

When microscopes are not available, both rock density and rock color can be a guide to the mineral composition. Refer to the Scheme for Igneous Rock Identification in the *Earth Science Reference Tables*. (R) This scheme shows a method of classifying and identifying igneous rocks. The color of an igneous rock is more like shade, or tone—it is the overall lightness or darkness of the total rock—not the actual color. Light-colored rocks are on the left side of the scheme and dark-colored rocks are on the right. Nonvesicular igneous rocks range from 2.7 g/cm^3 for low-density rocks (on the left side) to approximately 3.4 g/cm^3 for high-density rocks (on the right side). Thus both density and color hint at mineral composition when the minerals can't be seen, or if identification of the minerals is uncertain.

The percent mineral composition divides igneous rocks on the diagram into vertical columns of igneous rock families usually named for the coarse-grained member. An example would be the granite family, which includes granite, pegmatite, rhyolite, vesicular rhyolite, pumice, and some obsidian. The left, or granite side, of the chart is also the felsic side, which indicates a high aluminum (Al) and silicon (Si) content compared to the peridotite and dunite side on the right, which is mafic. Mafic rocks are higher in iron (Fe) and magnesium (Mg) and lower in silicon and aluminum. Note that all the minerals listed on this chart are silicates, with the oxygen-silicon tetrahedron as the basic component of the minerals' atomic structure.

Metamorphic Rocks

Rocks that form from changes in previously existing rocks due to heat, pressure, and/or mineral fluids without weathering or melting are **metamorphic rocks.** The previously existing rocks can be sedimentary, igneous, or other metamorphic rocks. The process of forming