Objectives

▸ Sequence the formation of sedimentary rocks.
▸ Explain the process of lithification.
▸ Describe 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

Formation of Sedimentary Rocks

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

Real-World Reading Link 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, 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 6.1** has been chemically and physically weathered.

![Figure 6.1](image) When exposed to both chemical and physical weathering, granite eventually breaks apart and might look like the decomposed granite shown here.

**Explain** which of the three common minerals—quartz, feldspar and mica—will be most resistant to weathering.
**Erosion** The removal and transport of sediment is called erosion. Figure 6.2 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. You will learn more about weathering and erosion in Chapter 7.

**Reading Check** Summarize what occurs during erosion.

---

Figure 6.2 Rocks and sediment are eroded and transported by the main agents of erosion—wind, moving water, gravity, and glaciers.

- **Wind**
- **Moving water**
- **Gravity**
- **Glaciers**

---
Model Sediment Layering

How do layers form in sedimentary rocks?
Sedimentary rocks are usually found 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 100 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 type of particles settle out first.
3. Describe what type of particles form the topmost layers.

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 6.3. 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.
**Compaction** Lithification begins with compaction. The weight of overlying sediments forces the sediment grains closer together, causing the physical changes shown in Figure 6.4. 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 found 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 (CaCO₃) or iron oxide (Fe₂O₃), grows between sediment grains as dissolved minerals precipitate out of groundwater. This process is illustrated in Figure 6.5.

**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.

---

**Figure 6.4** The flat shape of mud particles in mud causes them to compact tightly when subjected to the weight of overlying sediments. Round, sand-sized grains do not compact as well.

**Figure 6.5** Minerals precipitate out of water as it flows through pore spaces in the sediment. These minerals form the cement that glues the sediments together.

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*Incorporate information from this section into your Foldable.*
**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. To learn more about Earth science careers, visit glencoe.com.

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**Graded bedding** Bedding in which the particle sizes become progressively heavier and coarser toward the bottom 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 6.6**.

**Cross-bedding** Another characteristic feature of sedimentary rocks is cross-bedding. **Cross-bedding**, such as that shown in **Figure 6.7**, 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 6.8**. 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 6.8**.

---

**Figure 6.6** The graded bedding shown in this close-up of the Navajo Sandstone in Zion National Park records an episode of deposition during which the water slowed and lost energy.

**Figure 6.7** The large-scale cross-beds in these ancient dunes at Zion National Park were deposited by wind.
Figure 6.8 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.

To explore more about cross-bedding and ripple marks, visit glencoe.com.
Sorting and rounding Close examination of individual sediment grains reveals that some have jagged edges and some are rounded. When a rock breaks apart, the pieces are angular in shape. As the sediment is transported, individual pieces knock into each other. The edges are broken off and, over time, the pieces become rounded. The amount of rounding is influenced by how far the sediment has traveled. Additionally, the harder the mineral, the better chance it has of becoming rounded before it breaks apart and becomes microscopic in size. For example, the quartz sand on beaches is nearly round while carbonate sand, which is made up of seashells and calcite, is usually angular. Figure 6.9 shows the comparison between these types of sand.

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, it sometimes is buried before it decomposes. 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 turned into stone. 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 will learn more about fossils and how they form in Chapter 21. You learned firsthand how fossils can be used to interpret past events when you completed the Launch Lab at the beginning of this chapter.

Section 6.1 Assessment

Section Summary

- The processes of weathering, erosion, deposition, and lithification form sedimentary rocks.
- Clastic sediments are rock and mineral fragments produced by weathering and erosion. They are classified based on particle size.
- Sediments are lithified into rock by the processes of compaction and cementation.
- Fossils are the remains or other evidence of once-living things that are preserved in sedimentary rocks.
- Sedimentary rocks might contain features such as horizontal bedding, cross-bedding, and ripple marks.

Understand Main Ideas

1. **MAIN Idea** 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.
Types of Sedimentary Rocks

MAIN Idea Sedimentary rocks are classified by their mode of formation.

Real–World Reading Link 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 6.1 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 6.10. 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 6.1 to see how these rocks are named.
**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._

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**Classification of Sedimentary Rocks**

<table>
<thead>
<tr>
<th>Classification</th>
<th>Texture/Grain Size</th>
<th>Composition</th>
<th>Rock Name</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Clastic</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>coarse (≥ 2 mm)</td>
<td>Fragments of any rock type—quartz, chert and quartzite common</td>
<td>rounded angular</td>
<td>conglomerate breccia</td>
</tr>
<tr>
<td>medium (1/16 mm to 2 mm)</td>
<td>quartz and rock fragments quartz, k-spar and rock fragments</td>
<td>sandstone arkose</td>
<td></td>
</tr>
<tr>
<td>fine (1/256 mm–1/16 mm)</td>
<td>quartz and clay</td>
<td>siltstone</td>
<td></td>
</tr>
<tr>
<td>very fine (&lt; 1/256 mm)</td>
<td>quartz and clay</td>
<td>shale</td>
<td></td>
</tr>
<tr>
<td><strong>Biochemical</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>microcrystalline with conchooidal fracture</td>
<td>calcite (CaCO₃)</td>
<td>micrite</td>
<td></td>
</tr>
<tr>
<td>abundant fossils in micrite matrix</td>
<td>calcite (CaCO₃)</td>
<td>fossiliferous limestone</td>
<td></td>
</tr>
<tr>
<td>oolites (small spheres of calcium carbonate)</td>
<td>calcite (CaCO₃)</td>
<td>oolitic limestone</td>
<td></td>
</tr>
<tr>
<td>shells and shell fragments loosely cemented</td>
<td>calcite (CaCO₃)</td>
<td>coquina</td>
<td></td>
</tr>
<tr>
<td>microscopic shells and clay</td>
<td>calcite (CaCO₃)</td>
<td>chalk</td>
<td></td>
</tr>
<tr>
<td>variously sized fragments</td>
<td>highly altered plant remains, some plant fossils</td>
<td>coal</td>
<td></td>
</tr>
<tr>
<td><strong>Chemical</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fine to coarsely crystalline</td>
<td>calcite (CaCO₃)</td>
<td>crystalline limestone</td>
<td></td>
</tr>
<tr>
<td>fine to coarsely crystalline</td>
<td>dolomite (Ca,Mg)CO₃ (will effervesce if powdered)</td>
<td>dolostone</td>
<td></td>
</tr>
<tr>
<td>very finely crystalline</td>
<td>quartz (SiO₂)—light colored —dark colored</td>
<td>chert flint</td>
<td></td>
</tr>
<tr>
<td>fine to coarsely crystalline</td>
<td>gypsum (CaSO₄ • 2H₂O)</td>
<td>rock gypsum</td>
<td></td>
</tr>
<tr>
<td>fine to coarsely crystalline</td>
<td>halite (NaCl)</td>
<td>rock salt</td>
<td></td>
</tr>
</tbody>
</table>

---

**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 **Table 6.1** 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.
Fine-grained rocks  Sedimentary rocks consisting of silt- and clay-sized particles are called fine-grained rocks. Siltstone and shale are fine-grained clastic rocks. These rocks represent environments such as swamps and ponds 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 6.11. Unlike sandstone, fine-grained sedimentary rock has low porosity and often forms barriers that hinder the movement of groundwater and oil. Table 6.1 shows how these rocks are named.

Reading Check Identify the types of environments in which fine-grained rocks form.

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 6.12, 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, crystal grains precipitate out of solution and settle to the bottom. As a result, layers of chemical sedimentary rocks form, which are called evaporites. Evaporites most commonly form in arid regions and in drainage basins on continents that have low water flow. Because little freshwater flows into these areas, the concentration of dissolved minerals remains high. Even as more dissolved minerals are carried into the basins, evaporation continues to remove freshwater and maintain high mineral concentrations. Over time, thick layers of evaporite minerals can accumulate on the basin floor, as illustrated in Figure 6.12.
Biochemical sedimentary rocks

Biochemical sedimentary rocks are formed from the remains of once-living things. 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 6.13, these fossils can range from large-shelled organisms to microscopic, unicellular organisms. Not all limestone contains fossils. Some limestone has a crystalline texture, some consists of tiny spheres of carbonate sand, and some is composed of fine-grained carbonate mud. These are listed in Table 6.1.

Other organisms use silica to make their shells. These shells 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 6.1.

---

**Figure 6.13** Limestone can contain many different fossil organisms. Geologists can interpret where and when the limestone formed by studying the fossils within the rock.
Objectives

- **Compare and contrast** the different types and causes of metamorphism.
- **Distinguish** among metamorphic textures.
- **Explain** how mineral and compositional changes occur during metamorphism.
- **Apply** the rock cycle to explain how rocks are classified.

**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

---

### Metamorphic Rocks

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

**Real-World Reading Link** 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 6.14 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 or pressure becomes high enough, rocks melt and form magma. But what happens if the rocks do not reach the melting point? When high 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 6.14** 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.
**Metamorphic minerals** How do minerals change without melting? Think back to the concept of fractional crystallization, discussed in Chapter 5. 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 6.15** 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 6.16** 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 6.17**. This parallel alignment of minerals creates the layers observed in foliated metamorphic rocks.

---

**Figure 6.15** Metamorphic minerals form into many colors, shapes, and crystal sizes. Colors can be dark or bright and crystal form can be unique.

---

**Figure 6.16** Increasing grain size parallels changes in composition and development of foliation. Grain size is not a factor in nonfoliated rocks.

---

**Metamorphic Rock Identification Chart**

<table>
<thead>
<tr>
<th>Texture</th>
<th>Composition</th>
<th>Rock Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foliated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layered</td>
<td>Chlorite</td>
<td>Slate</td>
</tr>
<tr>
<td>Fine-grained</td>
<td>Mica</td>
<td>Phonolite</td>
</tr>
<tr>
<td>Coarse-grained</td>
<td>Quartz</td>
<td>Schist</td>
</tr>
<tr>
<td>Banded</td>
<td>Feldspar</td>
<td>Gneiss</td>
</tr>
<tr>
<td>Coarse-grained</td>
<td>Amphibole</td>
<td></td>
</tr>
<tr>
<td>Nonfoliated</td>
<td>Pyroxene</td>
<td></td>
</tr>
<tr>
<td>Fine- to coarse-grained</td>
<td>Quartz</td>
<td>Quartzite</td>
</tr>
<tr>
<td></td>
<td>Calcite or dolomite</td>
<td>Marble</td>
</tr>
</tbody>
</table>
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 6.18, 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. 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 6.18, is a mineral that commonly forms porphyroblasts.

Figure 6.18 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.
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 6.19** 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 6.19** show the mineral groups that form under different metamorphic conditions.

**Analysis**

1. What mineral is 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, basalt, and limestone.
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.
Regional metamorphism  When high 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, plus folding and deforming of the rock layers that make up the area. The mountain shown in Figure 6.14 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 6.20 shows zones of different minerals surrounding an intrusion. Because temperature decreases with distance from an intrusion, metamorphic effects also decrease with distance. Recall from Chapter 5 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 6.21 is the result of hydrothermal metamorphism.
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 6.22 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.
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; sedimentary rocks form from cemented or precipitated 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 6.23. The arrows represent the different processes that change rocks into different types.

Section 6.3 Assessment

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. **MAIN Idea** 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?