3
Rocks

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Chapter Introduction

These beach pebbles along Lake MacDonald in Glacier National Park, Montana, were eroded from the surrounding mountains by glaciers and streams, transported downslope by gravity, and rounded by wave energy on the lake shoreline.
Earth is solid rock to a depth of 2,900 kilometers, where the mantle meets the liquid outer core. Even casual observation reveals that rocks are not all alike. The great peaks of the Sierra Nevada in California are hard, strong granite. The red cliffs of the Utah desert are soft sandstone. The top of Mount Everest is limestone containing the fossil remains of small marine invertebrates.

The marine fossils atop Mount Everest tell us that this limestone formed in the sea. What forces lifted the rock to the highest point of the Himalayas? Where did the vast amounts of sand in the Utah sandstone come from? How did the granite of the Sierra Nevada form?

All of these questions ask about the processes that formed the rocks and changed them throughout geologic history. In this chapter we will study rocks, what they are made of,
3-1 Rocks and the Rock Cycle

A rock is a solid aggregate of one or more minerals. Based on how the rocks form, geologists define three main categories: igneous rocks, sedimentary rocks, and metamorphic rocks.

Earth’s interior is hot and dynamic. The high temperature that exists within a few hundred kilometers of the surface can cause solid rock to melt, forming a molten liquid called magma (Molten rock generated from melting of any rock in the subsurface; cools to form igneous rock.) Because the liquid magma is less dense than the surrounding solid rock, the magma rises slowly toward Earth’s surface. As it rises, the magma cools. igneous rock (Rock that forms when magma cools and crystallizes.) forms when cooling magma solidifies.

All rocks may seem permanent and unchanging over a human lifetime, but this apparent permanence is an illusion created by our short observational time frame. Over geologic time, water and air attack rocks of all kinds at Earth’s surface through the process called weathering (The decomposition and disintegration of rocks and minerals at Earth’s surface by chemical and physical processes.), breaking them down into smaller particles. These particles—including gravel, sand, clay, and all other fragments weathered and eroded from rock—are transported away from the site of weathering by streams, glaciers, wind, and gravity. Eventually the particles accumulate in loose, unconsolidated layers called sediment (Solid rock or mineral fragments that are transported and deposited by wind, water, gravity, or ice; that are weathered by natural forces, precipitated by chemical reactions, or secreted by organisms; and that accumulate in loose, unconsolidated layers.). Sand on a beach and mud on a lake bottom are examples of sediment. Sedimentary rock (Rock formed when sediment becomes compacted and cemented through the process of lithification.) forms when sediment particles becomes cemented or compacted into solid rock.

Weathering processes also form dissolved ions such as sodium, calcium, and chloride. These ions are transported away from the site of weathering by streams and groundwater. Many households contain water softeners to remove these dissolved ions so they don’t precipitate and clog the home's plumbing system.

Most of the dissolved ions formed by weathering eventually are carried to the sea. There, marine organisms such as clams, oysters, and corals extract dissolved calcium from seawater. They combine the calcium with carbon dioxide that dissolves in seawater from Earth’s atmosphere, and use it to form their shells and other hard parts. After the organisms die, the remains of those shells accumulate and become the sedimentary rock called limestone. Thus, limestone, one of the most common sedimentary rocks, forms by direct interactions among the geosphere, the hydrosphere, the biosphere, and the
A **metamorphic rock** (A rock formed when igneous, sedimentary, or other metamorphic rocks recrystallize in response to elevated temperature, increased pressure, chemical change, and/or deformation.) forms when heat, pressure, or hot water alters any preexisting rock. For example, when rising magma intrudes the Earth’s crust, it heats the rock around it. Although the heat may not be sufficient to melt rock surrounding the magma, it can bring about other changes. For example, the mineral crystals in the heated rock may grow or change their internal arrangement. Such alterations in the size, shape, and arrangement of mineral crystals within the rock are changes in the rock’s **texture** (The size, shape, and arrangement of mineral grains, or crystals, in a rock.). In addition, temperature and pressure within the Earth’s crust may cause entirely different mineral types to grow that are stable at those changed temperatures and pressures. Thus, the process of metamorphism can change both the texture and mineral types within a preexisting rock. Unlike igneous rocks, however, metamorphic rocks form without completely melting.

No rock is permanent over geologic time; instead, all rocks undergo processes that change them from one of the three rock types to another. This continuous process is called the **rock cycle** (The sequence of events in which rocks are formed, destroyed, altered, and reformed by geological processes.) (Figure 3.1). For example, as sediment accumulates and is buried, it typically cements together to form a sedimentary rock. If sedimentary rock at the bottom of the accumulation is buried deeply enough, the rising temperature and pressure will cause it to convert to a metamorphic rock as it undergoes changes in texture and mineral composition. With additional burial and temperature increase, the metamorphic rock can melt, forming magma. The magma will then rise in the crust, slowly cool, and solidify to become igneous rock. Millions of years later, movement of Earth’s crust might raise the igneous rock to the surface, where it will weather to form sediment. Rain and streams will then wash the sediment into a new basin, renewing the cycle.

**Figure 3.1**

The rock cycle shows that rocks change over geologic time. The arrows show paths that rocks can follow as they change.
The rock cycle does not follow a set order, and can take many different paths. For example, all three rock types can melt to form magma and, eventually, an igneous rock. Similarly, all three rock types can be weathered to form sediment or can be metamorphosed through changes in texture and mineral composition. The term “rock cycle” simply expresses the idea that rocks are not permanent, but change over geologic time.
The rock cycle illustrates several types of Earth systems interactions—interactions among rocks, the atmosphere, the biosphere, and the hydrosphere. Rain and air, aided by acids and other chemicals secreted by plants, decompose solid rocks to form large amounts of clay and other sediment. During these processes, water and atmospheric gases react chemically and become incorporated into the clay. Thus, these processes transfer water and air from the atmosphere and hydrosphere to the solid minerals of the geosphere. More rain then washes the clay and other sediment into streams, which carry it to a sedimentary basin where the clay is deposited. Recall from Chapter 1 that solar energy drives the hydrologic cycle. So sunlight evaporates moisture to form rain, which in turn feeds flowing streams. But these same processes are also part of the rock cycle, illustrating once again that all Earth processes interact.

The rock cycle is also driven by Earth’s internal heat. For example, when a sedimentary basin sinks under the weight of additional sediment, the deeper layers become heated and metamorphosed by Earth’s heat. The same heat may melt the rocks to produce magma. But then the magma rises upward and perhaps even erupts onto Earth’s surface from a volcano. In this way, heat is transferred from Earth’s interior to the atmosphere.

Throughout this chapter, we will emphasize these and other interactions among the atmosphere, biosphere, hydrosphere, and rocks of the geosphere to illustrate the point that those systems continuously exchange both energy and material so that Earth functions as a single, integrated system.

3-2 Igneous Rocks

3-2a Magma: The Source of Igneous Rocks

If you drilled a well deep into the middle of one of Earth’s continents, you would find that the temperature within the crust rises about 30°C for every kilometer of depth. In the mantle between depths of 100 and 350 kilometers, the temperature is so high that rocks in some areas melt to form magma. Depending on its chemical composition and the depth at which it forms, the temperature of magma varies from about 600°C to 1,400°C. As a comparison, an iron bar turns red hot at about 600°C and melts at slightly over 1,500°C.

When rock melts, the resulting magma expands by about 10 percent, so it is less dense than the rock around it and therefore rises as it forms—much as a hot air balloon ascends in the atmosphere. When magma rises, it enters the cooler environment near Earth’s surface, where it solidifies to form solid igneous rock.
3-2b Types of Igneous Rocks

Some igneous rock forms when magma solidifies within Earth’s crust; other igneous rock is created when magma erupts onto the surface. When magma solidifies, it usually crystallizes to form minerals. The size, shape, and arrangement of these mineral crystals are referred to as the rock’s texture. Although some igneous rocks consist of mineral crystals that are too small to be seen with the unaided eye, others are made up of thumb-sized, or even larger, crystals (Table 3.1).

<table>
<thead>
<tr>
<th>Name of Texture</th>
<th>Crystal Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glassy</td>
<td>No mineral crystals (obsidian)</td>
</tr>
<tr>
<td>Very finely crystalline</td>
<td>Too fine to see with unaided eye</td>
</tr>
<tr>
<td>Finely crystalline</td>
<td>Up to 1 millimeter</td>
</tr>
<tr>
<td>Medium crystalline</td>
<td>1 to 5 millimeters</td>
</tr>
<tr>
<td>Coarsely crystalline</td>
<td>More than 5 millimeters</td>
</tr>
<tr>
<td>Porphyry</td>
<td>Relatively large crystals in a finely crystalline matrix</td>
</tr>
</tbody>
</table>

Table 3.1

Igneous Rock Textures Based on Crystal-Size

Extrusive (Volcanic) Rocks

When magma rises all the way through the crust to erupt onto Earth’s surface, it forms extrusive igneous rock (Igneous rock formed from material that has erupted through the crust onto the surface of Earth; usually finely crystalline. Also called volcanic rock), also called volcanic rock. Lava (Fluid magma that flows onto Earth’s surface from a volcano or fissure. Also, the rock formed by solidification of the same fluid magma) is fluid magma that flows from a crack or a volcano onto Earth’s surface. The term also refers to the rock that forms when lava cools and becomes solid.
After lava erupts onto the relatively cool Earth surface, it solidifies rapidly—in a period ranging from a few days to a few years. Crystals form but do not have much time to grow. As a result, many volcanic rocks consist of crystals too small to be seen with the unaided eye. Basalt is a common, very finely crystalline volcanic rock.

If erupting lava encounters glacial ice or cold seawater, it may solidify within a few hours of erupting. Because the magma hardens so quickly, the atoms have no time to align themselves to form crystals. As a result, the atoms are frozen into a random chaotic pattern, as happens in glass. Volcanic glass is called obsidian (Figure 3.2).

**Figure 3.2**

Obsidian is natural volcanic glass. It contains no crystals. This sample is about 15 centimeters wide.

If magma rises slowly through the crust before erupting, some crystals may grow, while most of the magma remains molten. If this mixture of magma and crystals then erupts onto the surface, the magma solidifies quickly, forming porphyry, a rock with large crystals, called phenocrysts, embedded in a fine-grained matrix (Figure 3.3).

**Figure 3.3**

Porphyry is an igneous rock containing large crystals, called phenocrysts, embedded in a fine-grained matrix. This is a rhyolite porphyry.
Intrusive (Plutonic) Rocks

When magma solidifies within the crust, without erupting to the surface, it is an intrusive igneous rock (A rock formed when magma solidifies within Earth’s crust without erupting to the surface; usually medium to coarsely crystalline. Also called plutonic rock.), also called plutonic rock, named after the Greek god of the underworld. The rock overlying the magma insulates it like a thick blanket, providing hundreds of thousands, or even millions, of years for the magma to crystallize. As a result, most plutonic rocks are medium-to-coarsely crystalline. Granite, the most abundant rock in continental crust, is a medium or coarsely crystalline plutonic rock. The crystals in granite are clearly visible. Many are a millimeter or so across, although some crystals may be much larger.

Chapter 3: Rocks: 3-2c Naming and Identifying Igneous Rocks
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3-2c Naming and Identifying Igneous Rocks

Geologists have different names for igneous rocks based on their minerals and texture. Let’s take for example two rocks consisting mostly of feldspar and quartz. Medium or coarsely crystalline igneous rock made up of these minerals is called granite. When igneous rock with these minerals is very finely crystalline, it is called rhyolite. You can see the difference in the two panels of Figure 3.4. The same magma that solidifies slowly within the crust to form granite can also erupt onto Earth’s surface to form rhyolite.

Figure 3.4

(A) This sample of granite has crystals the size of a U.S. quarter. (B) Rhyolite with visible crystals of smoky quartz and feldspar set in a very finely crystalline matrix. U.S. penny for scale.
Like granite and rhyolite, most common igneous rocks are classified in pairs, with the two members of a pair containing the same minerals but with different crystal sizes. The crystal size depends mainly on whether the rock is volcanic (finely crystalline) or plutonic (coarsely crystalline).

Once you learn to identify the rock-forming minerals, it is easy to name a coarsely crystalline plutonic rock because the minerals are large enough to see. It is more difficult to name many volcanic rocks, because the minerals are too small to identify. A field geologist often uses color to name a volcanic rock. Rhyolite is usually light in color: white, tan, red, and pink are common. Many andesite rocks are gray or green. Basalt is commonly black. Because of their tiny crystal sizes, the minerals in volcanic rocks often require specialized laboratory analyses for positive identification.

Chapter 3: Rocks: 3-2d Common Igneous Rocks
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3-2d Common Igneous Rocks

Before proceeding with our discussion, you should become familiar with some terminology. Geologists commonly use the terms *basement rock*, *bedrock*, *parent rock*, and *country rock*. **Bedrock** (The solid rock that lies beneath soil or unconsolidated sediments; it can be igneous, metamorphic, or sedimentary) is the solid rock that lies beneath soil or unconsolidated sediments. It can be igneous, metamorphic, or sedimentary. **Parent rock** (Any original rock before it is changed by weathering, metamorphism, or other geological processes) is any original rock before it is changed by weathering, metamorphism, or other geological processes. The rock that is already in an area and is cut into by intrusive igneous rock or by a mineral deposit is called **country rock** (The older rock already in an area, cut into by a younger igneous intrusion or mineral deposit). **Basement rock** (The older igneous and metamorphic rock that lies beneath the thin layer of sedimentary rocks and soil covering much of Earth’s surface; forms the “basement” of the crust) is the igneous and metamorphic rock that lies beneath the thin layer of sediment and sedimentary rocks covering much of Earth’s surface, thus forming the “basement” of the crust.
3-2e Granite and Rhyolite

As discussed above, granite contains mostly feldspar and quartz. Small amounts of black biotite or hornblende often give it a speckled appearance. Granite (and metamorphosed granite) is the most common rock in continental crust. It is found nearly everywhere as basement rock, beneath the relatively thin veneer of sedimentary rocks and soil that covers most of the continents. Granite is hard and resistant to weathering; it forms steep, sheer cliffs in many of the world's great mountain ranges. Mountaineers prize granite cliffs for the steepness and strength of the rock.

As granitic magma (magma with the chemical composition of granite) rises through Earth's crust, some of it may erupt from a volcano to form rhyolite, while the remainder solidifies beneath the volcano, forming granite. Most obsidian forms from magma with a granitic (rhyolitic) composition.

3-2f Basalt and Gabbro

Basalt consists of approximately equal amounts of plagioclase feldspar and pyroxene. It makes up most of the oceanic crust, as well as huge basalt plateaus on continents. Gabbro is the plutonic equivalent of basalt; it is mineralogically identical but consists of larger crystals. Gabbro is uncommon at Earth's surface, although it is abundant in deeper parts of the oceanic crust, where basaltic magma crystallizes slowly.

3-2g Andesite and Diorite

Andesite is a volcanic rock intermediate in composition between basalt and granite. It is commonly gray or green and consists of plagioclase feldspar and dark minerals (usually biotite, amphibole, or pyroxene). It is named for the Andes Mountains, the volcanic chain on the western edge of South America, where andesite is abundant. Because it is volcanic, andesite is typically very fine grained. Diorite is the plutonic equivalent of andesite. It forms from the same magma as andesite and, consequently, often underlies andesitic mountain chains such as the Andes.
3-2h Peridotite and Komatiite

Peridotite is an ultramafic (rich in magnesium and iron) igneous rock that makes up most of the upper mantle but is rare in Earth’s crust. It is coarse grained and composed of olivine and small amounts of pyroxene, amphibole, or mica, but no feldspar. Komatiite is the finely crystalline, extrusive equivalent of peridotite. Geologists think that it was the material of the earliest crust that formed as the molten planet cooled more than 4 billion years ago. Only a few traces of this primordial crust are known to exist today.

3-3 Sedimentary Rocks

Over geologic time, the atmosphere, biosphere, and hydrosphere weather rock, breaking it down to gravel, sand, silt, clay, and ions dissolved in water. Weathering of rocks occurs by both chemical and physical processes. Glaciers, flowing water, gravity, and wind all erode the rock, transport the rock fragments downslope, and deposit them at lower elevations. Once deposited and buried, the loose, unconsolidated sediment becomes compacted and cemented—a process called lithification (The process by which loose sediment is converted to solid rock.)—and forms sedimentary rock.

Dissolved ions resulting from weathering also are transported downslope, commonly all the way to the sea, where the ions are concentrated. Marine organisms such as clams, snails, certain kinds of green algae, and corals use some of these ions to form shells and other hard parts. After the organisms die, these hard parts accumulate to form limestone. Other ions can react chemically to produce a solid salt, through the process of precipitation (A chemical reaction that produces a solid salt, called a precipitate, from a liquid solution.) . For example, the mineral halite (rock salt) precipitates from a lake on the floor of Death Valley (Figure 3.12).

Sedimentary rocks make up only about 5 percent of Earth’s crust. However, because they form on Earth’s surface, sedimentary rocks are widely spread in a thin veneer over underlying igneous and metamorphic rocks. As a result, they cover about 75 percent of continents.

Sedimentary rocks are broadly divided into four categories:

1. Clastic sedimentary rock is composed of particles of weathered rocks, such as sand grains and pebbles, called clasts, which have been transported, deposited, and lithified. (The generic term clastic refers to any rocks that are composed of fragments of older rocks.) This category includes conglomerate, sandstone, and shale. Clastic
sedimentary rock makes up about 85 percent of all sedimentary rock (Figure 3.5).

2. *Organic sedimentary rock* consists of the lithified remains of plants or animals. Coal is an organic sedimentary rock that contains such a high percentage of decomposed and compacted plant remains that the rock itself will burn.

3. Chemical sedimentary rock forms by direct precipitation of minerals from solution. Rock salt, for example, forms when halite precipitates from evaporating seawater or saline lake water.

4. *Bioclastic sedimentary rock* is composed of broken shell fragments and similar remains of living organisms. The fragments are clastic, but they have a biological origin. Many limestones are formed from broken shells and thus are bioclastic sedimentary rocks.

**Figure 3.5**

Earth's sedimentary rocks: Shale, siltstone, and sandstone are clastic rocks that make up about 85 percent of all sedimentary rocks. Limestone and other sedimentary rocks make up less than 15 percent.
Clastic Sedimentary Rocks

Clastic sediment is called gravel, sand, silt, or clay, in order of decreasing particle size. Table 3.2 shows the main sediment particle sizes and their corresponding diameters. As clastic particles ranging in size from boulders to coarse silt tumble downstream, their sharp edges are worn off and they become rounded, like those in Figure 3.6. Finer silt and clay do not round effectively because they are so small and light that water and wind cushion them as they are buffeted along.

<table>
<thead>
<tr>
<th>Sediment Particle Name</th>
<th>Sediment Particle Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boulder</td>
<td>&gt; 258</td>
</tr>
<tr>
<td>Cobble</td>
<td>64–256</td>
</tr>
<tr>
<td>Pebble</td>
<td>4–64</td>
</tr>
<tr>
<td>Granule</td>
<td>2–4</td>
</tr>
<tr>
<td>Sand</td>
<td>.0625–2</td>
</tr>
<tr>
<td>Silt</td>
<td>.0039–.0625</td>
</tr>
<tr>
<td>Clay</td>
<td>&lt; 0.0039</td>
</tr>
</tbody>
</table>

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Figure 3.6

Boulders and rocks collide as they move downstream. The collisions wear away the sharp edges, producing rounded stones.
If you hold a pile of sand in your hand and dribble water onto it, the water will soak into the empty zone—called **pore space** (The empty space between particles of rock, sediment, or soil.)—among the sand grains (Figure 3.7). Commonly, sand and similar sediment have about 20 to 40 percent pore space. As we will see in Chapter 5, this pore space is very important because it is where economic quantities of water, petroleum, and natural gas typically occur.

As sediment accumulates and is buried, it is compressed by the weight of the overlying layers. The compression partially collapses the pore spaces between sediment grains, forcing water out (Figure 3.7B). This process is called **compaction** (Increased packing together of sedimentary grains, usually resulting from the weight of overlying sediment; causes a decrease in porosity and contributes to lithification.)

**Figure 3.7**

(A) Pore space is the open space between sediment grains. (B) Compaction squashes the grains together, reducing the pore space and lithifying the sediment by interlocking the grains. (C) Cement fills the remaining pore space, lithifying the sediment by gluing the grains together.
As sediment is buried and compacted, groundwater slowly circulates through the remaining pore space. This water commonly contains dissolved ions that can precipitate in the pores, forming cement that binds the clastic grains firmly together into a hard rock. Calcite, quartz, and iron oxides are the most common cements in sedimentary rocks. (Figure 3.7C).

The time required for lithification of sediment varies greatly. In some heavily irrigated areas of Southern California, calcite has precipitated from irrigation water to cement soils within only a few decades. In the northern Rocky Mountains, calcite has cemented some glacial deposits that are less than 20,000 years old. In contrast, sand and gravel deposited on the coastal plain of New Jersey as long ago as 95 million years can still be dug with a hand shovel.

**Conglomerate** (a clastic sedimentary rock that consists of lithified gravel) is lithified gravel. Each clast in a conglomerate is usually much larger than the individual mineral grains in the clast. In many conglomerates, the clasts may be fist sized or even larger and therefore retain most of the characteristics of the parent rock. If enough is known about the geology of an area where conglomerate is found, it may be possible to identify exactly where the clasts originated. For example, a granite clast probably came from nearby granite bedrock.
Figure 3.8

Conglomerate is lithified gravel. The individual clasts are clearly visible in this conglomerate from southwestern Montana. Lens cap for scale.

The next time you walk along a gravelly stream bed, look carefully at the gravel. You will probably see sand or silt trapped among the larger clasts. In a similar way, most conglomerates contain fine sediment among the large clasts.

Sandstone consists of lithified sand grains (Figure 3.9). The sand forms from the physical and chemical breakdown of preexisting rock. For example, weathering of granite typically produces sand-sized grains of quartz, feldspar, and other minerals. Streams, wind, glaciers, and gravity all can carry downslope sand formed by weathering. Sand grains carried in streams and by wind repeatedly undergo collisions as they bounce along. These impacts wear the sharp edges off of each grain, causing it to become rounded. Eventually, the sand grains accumulate to form a deposit of sand. Over time, the deposit compacts and lithifies to form sandstone. Many sandstones consist predominantly of rounded quartz grains, because this hard mineral resists physical and chemical breakdown and therefore is concentrated by long periods of weathering and transport.
Figure 3.9

Sandstone is lithified sand. (A) Sandstone cliffs and spires in Arches National Park, Utah. (B) Photomicrograph of a thin slice of sandstone showing well-rounded, sand-sized grains of quartz cemented together with calcite. Scale bar is one millimeter long.

Shale (A clastic sedimentary rock that consists of lithified clay minerals and minor amounts of silt-sized quartz, feldspar, other minerals, and organic particles. The organic material in shale is the source of most oil and natural gas.) is a clastic sedimentary rock that consists mostly of tiny clay minerals and lesser amounts of silt and organic particles.
Shale can vary widely in color, ranging from red to green to black. When weathered, some shale splits easily along very fine layering, called fissility. Such fissile shale usually is dark-colored due to the presence of abundant organic matter. As it is buried, this organic matter can convert to oil and gas, which is slowly expelled from the shale and rises towards the surface through pore spaces in the rock. In Chapter 5, we will learn how recent technological developments that permit the direct drilling and hydraulic fracturing ("fracking") of organic-rich black shale has resulted in entirely new sources of oil and gas.

**Figure 3.10**

Shale consists of lithified clay and silt and typically is thinly layered, as is this shale sample from southwestern Wyoming.

**3-3b Organic Sedimentary Rocks**

Organic sedimentary rocks form by lithification of the remains of plants and animals. Coal is perhaps the most obvious example of an organic sedimentary rock, containing so much organic matter that the rock will burn. Coal forms from the accumulation of **peat** (a loose, unconsolidated, brownish mass of partially decayed plant matter; a precursor to coal) in swamps and similar environments where dead plants accumulate faster than they can be broken down by decay. As peat is buried and compacted by overlying sediments, it is lithified and converts to coal.

A more common organic sedimentary rock is chert, which is composed of very finely-crystalline quartz. Chert comes in many different colors and is one of the earliest geologic resources. Flint, a dark gray to black variety, was frequently used by humans for arrowheads, spear points, scrapers, and other tools chipped to hold a fine edge.
Chert typically forms in two varieties: **bedded chert** occurs as sedimentary beds or layers; **nodular chert** is found as irregularly shaped lumps called “nodules” within other sedimentary rocks (Figure 3.11). Microscopic examination of bedded chert often shows that it contains the remains of tiny marine organisms whose skeletons are composed of silica rather than calcium carbonate. The organisms extract silica from seawater to form their skeletons and accumulate in layers on the seafloor when they die, eventually forming bedded chert. In contrast, some nodular chert appears to form by precipitation from silica-rich groundwater, typically in limestone or rhyolite.

**Figure 3.11**

Red nodules of chert in light-colored limestone. The nodules shown here are fist sized.

Some common elements in rocks and minerals—such as calcium, sodium, potassium, and magnesium—dissolve during chemical weathering and are carried by groundwater and streams downslope. Most streams eventually reach the sea, but some streams are landlocked and end instead in a lake with no outlet, such as the Great Salt Lake in Utah. No streams exit such lakes; rather, water escapes only by evaporation or downward seepage. When the water evaporates, salts remain behind and the lake water becomes steadily saltier. Evaporites are rocks that form when evaporation concentrates the salts to the point at which they precipitate from solution (Figure 3.12). The same process can occur if ocean water is trapped in coastal or inland basins where it can no longer mix with the open sea.
**3-3d Bioclastic Sedimentary Rocks**

**Carbonate rocks** (bioclastic sedimentary rocks composed of the carbonate minerals (minerals based on the $\text{CO}_3^{2-}$-anion)) are primarily made up of the carbonate minerals calcite and dolomite, described in Chapter 2. Calcite-rich rocks are called limestone, whereas rocks rich in dolomite are referred to as dolomite or dolostone.

Dissolved calcium ions are released into water during the chemical weathering of calcium-bearing rocks. The carbonate anion forms when atmospheric carbon dioxide gas dissolves in water. Seawater contains large quantities of both dissolved calcium and carbon dioxide. Clams, snails, corals, some types of algae, and a variety of other marine organisms convert dissolved calcium and carbonate ions to shells and other hard body parts. When these organisms die, waves and ocean currents break the shells into fragments that can range in size from boulders, in the case of some large corals, to clay-sized particles, in the case of certain types of algae that secrete calcium carbonate. A rock formed by lithification of such sediment is called bioclastic limestone, indicating that it forms by both biological and clastic processes.

Most limestones are bioclastic. **Coquina** (a limestone made up entirely of shell fragments.)
is bioclastic limestone consisting wholly of coarse shell fragments cemented together. Chalk (a very fine-grained limestone made up of the remains of tiny marine microorganisms) is a very fine-grained, soft, white bioclastic limestone made of the shells and skeletons of microorganisms that float near the surface of the oceans. When they die, their remains sink to the bottom and accumulate to form chalk.

**Figure 3.13**

A close-up of shell fragments in limestone. Most limestone is composed of lithified shell fragments and other remains of marine organisms.

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**3-3e Carbonate Rocks and Global Climate**

Carbon dioxide is a greenhouse gas that traps heat in the atmosphere. Limestone is a hard, solid rock. Although it may seem counterintuitive, limestone rock is formed largely from carbon dioxide gas. Atmospheric carbon dioxide dissolves in seawater and then combines with dissolved calcium to form limestone rock, so formation of limestone removes carbon dioxide from both the seas and the air.

In Chapter 1 we mentioned briefly that Earth’s outer shell is broken into several segments called tectonic plates. The plates float on the weak, plastic mantle below and glide across Earth, moving continents and oceans. You will learn in Chapter 6 that after a tectonic plate moves thousands of kilometers across Earth’s surface, it eventually sinks deep into the mantle. In some instances, a sinking plate may carry limestone into the mantle, removing large amounts of carbon from Earth’s surface and sequestering it in the deep mantle. In other cases, limestone on a sinking tectonic plate may become heated to the point that
carbon is recycled back into the atmosphere as carbon dioxide emitted during volcanic eruptions. In these ways the greenhouse gas is cycled between surface limestone, deep-mantle rocks, and the atmosphere. Thus, interactions among limestone, the carbon dioxide in the atmosphere, and the carbon dioxide dissolved in the oceans are important determinants of global climate.

Chapter 3: Rocks: 3-3f Physical Sedimentary Structures
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3-3f Physical Sedimentary Structures

Nearly all sedimentary rocks contain sedimentary structures (Any feature of sedimentary rock formed by physical processes during or shortly after deposition; examples include stratification, cross-bedding, ripple marks, and tool marks.)—physical features that developed during or shortly after deposition of the sediment. These structures help us understand how the sediment was transported and deposited. Because sedimentary rocks form at Earth’s surface, sedimentary structures and other features of sedimentary rocks also contain clues about environmental conditions at Earth’s surface when the rocks formed.

The most obvious and common sedimentary structure is bedding (Layering that develops as sediments are deposited; also called stratification.) , or stratification—layering that develops as sediment is deposited (Figure 3.14). Bedding forms because sediment accumulates layer by layer, with short pauses in sediment deposition represented by the surfaces separating individual beds.

Figure 3.14

Sedimentary beds exposed in Capitol Reef National Park, Utah.
Many beds of sandstone contain cross-bedding (A sedimentary structure in which wind or water deposits sets of beds that are inclined to the main sedimentary layering.), in which sets of small beds are inclined to the main sedimentary layering (Figure 3.15). Cross-bedding forms in many environments where wind or water transports and deposits sediment. It is very common in sands deposited by wind, streams, and some ocean currents. The wind and water currents can organize the sand into semiparallel ridges called dunes. Continued flow of water and wind cause sand grains to be eroded off the more gently-sloping side of the dune that faces upstream, and these sand grains travel in the current to the brink of the dune. There, the sediment avalanches down the steep side of the dune that faces downstream. The inclined layer of sediment that results from the avalanche forms a cross-bed. Multiple such avalanches form sets of cross-beds (Figure 3.15B).

**Figure 3.15**

(A) Cross-bedding preserved in lithified ancient sand dunes in Pariah Canyon, Utah. (B) A modern sand dune at Guerro Negro, Baja California, Mexico (left) and an oblique cross-sectional view through a sand dune (right). (C) The development of cross-bedding as the prevailing wind direction changes.
Ripple marks (Small, semiparallel ridges and troughs formed mostly in sand by wind, water currents, or waves; often preserved when the sediment is lithified.) are small ridges and troughs that are also formed in sand or coarse silt by moving water or wind. You commonly see them in shallow streams and around lake shorelines. Ripple marks are also
commonly preserved in sandstone. They can form either by currents moving in a single
direction, as in a stream, or from currents moving back and forth, as in a shallow lake
where sand on the bottom is pushed forward and back by waves on the lake surface.

**Mud cracks** (Irregular polygonal downward-tapering fractures that develop when mud
dries; may be preserved when the mud is lithified.) are irregular polygonal downward-
tapering cracks that form when mud shrinks as it dries out. They indicate that the mud
dried up after being deposited in water. Mud cracks are common in river floodplains, where
mud deposited by a flood eventually dries out when the floodwaters recede.

In some place, very delicate sedimentary structures are preserved in rocks. For example,
geologists have found in sedimentary rocks over a billion years old the imprints of
raindrops that fell on a muddy surface.

**Fossils** (The imprint, remains, or any other trace of a plant or animal preserved in rock.)
and **biogenic structures** (Any physical trace left in the sedimentary record by a fossil
organism; includes tracks, trails, burrows, and root casts.) include remains and traces of
plants or animals preserved in rock—any evidence of past life. Fossils include remains of
shells, bones, or teeth; whole bodies preserved in shale, amber, or ice; and a variety of
tracks, trails, and burrows. Fossils are discussed further in Chapter 4.

Chapter 3: Rocks: 3-4 Metamorphic Rocks
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### 3-4 Metamorphic Rocks

A potter forms a delicate vase from moist clay. She places the soft piece in a kiln and slowly
heats it to 1,000°C. As temperature rises, the clay minerals decompose. Atoms from the
clay then recombine to form new minerals that make the vase strong and hard. The
breakdown of the clay minerals, growth of new minerals, and hardening of the vase all
occur without melting the solid materials.

**Metamorphism** (The process by which rocks change texture and mineral content in
response to variations in temperature, pressure, chemical conditions, and/or deformation.)
(from the Greek words for “changing form”) is the process by which rising temperature
and pressure, or changing chemical conditions, transform rocks and minerals.
Metamorphism occurs in solid rock, like the transformations in the vase as the potter fires
it in her kiln. Small amounts of water and other fluids speed up the metamorphic mineral
reactions, but the rock remains solid as it changes. Metamorphism can change any type of
parent rock: sedimentary, igneous, or even another metamorphic rock.

A mineral that does not decompose or change in other ways, no matter how much time
passes, is a “stable” mineral. A stable mineral can become unstable when environmental
conditions change. Three types of environmental change affect mineral stability and cause
metamorphism: rising temperature, rising pressure, and changing chemical composition
(usually caused by an influx of hot water). For example, when the potter put the clay in her
kiln and raised the temperature, the clay minerals decomposed because they became
unstable at the higher temperature. The atoms from the clay then recombined to form new minerals that were stable at the higher temperature. Similarly, if hot water seeping through bedrock carries new chemicals to a rock, those chemicals may react with the rock’s original minerals to form different minerals that are stable in the new chemical environment. Thus, metamorphism occurs because each mineral is stable only within a certain range of temperature, pressure, and chemical environment. If temperature or pressure rises above that range, or if chemicals are added or removed from the rock, the rock’s original minerals may decompose and their components recombine to form new minerals that are stable under the new conditions.

Chapter 3: Rocks: 3-4a Metamorphic Grade

3-4a Metamorphic Grade

The **metamorphic grade** (The intensity of metamorphism that formed a rock; the maximum temperature and pressure attained during metamorphism.) of a rock is the intensity of metamorphism that formed it. Temperature is the most important factor in metamorphism, and therefore grade closely reflects the temperature of metamorphism. Because temperature increases with depth in Earth, a general relationship exists between depth and metamorphic grade (**Figure 3.16**). Low-grade metamorphism occurs at shallow depths, less than 10 kilometers beneath the surface, where temperature is no higher than 300°C to 400°C. Medium-grade conditions, where temperatures are between 400°C and 600°C, exist at depths between about 10 and 40 kilometers. High-grade conditions are found deep within the continental crust and in the upper mantle, 40 to 55 kilometers below Earth’s surface. The temperature here is 600°C to 800°C, close to the melting point of rock. High-grade conditions can develop at shallower depths, however, in rocks adjacent to hot magma. For example, today metamorphic rocks are forming beneath Yellowstone Park, where hot magma lies close to Earth’s surface.

**Figure 3.16**

Metamorphic grade increases with depth because temperature and pressure rise with depth. The blue arrow traces the path of increasing temperature and pressure with depth in crust typically found in a stable continental interior.
Virtual Field Trip

Sedimentary Rocks: Formation and Correlation

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**Ready to Go!**

On this virtual field trip we will visit Arches and Capitol Reef National Parks in Utah. The rocks that make up the brightly colored walls, arches, and towers are among the most common sedimentary rocks—sandstone, shale, and mudstone—described in Section 3-3 ("Sedimentary Rocks") above. The scenic exposures allow us to see interesting and important features and principles common to all sedimentary rocks, including sedimentary layering, the principle of superposition, and the principle of original horizontality. The origin of sedimentary layering is described under “Physical Sedimentary Structures” above. The principles of superposition and original horizontality are described in Chapter 4, in Section 4-3 ("Relative Geologic Time"). Refer to these topics in this chapter and Chapter 4 as you take this trip. We will also see examples of the processes that weather and erode all kinds of rocks, which are described in Section 10-1 ("Weathering and Erosion"), in Chapter 10 of this book.

**Goals of the Trip**

Some of the goals of this trip are to understand that:

1. Sedimentary rocks are layered, or “stratified,” because sediments are deposited on the Earth’s surface in successive layers.

2. Sedimentary rocks are progressively younger in an upward direction because each layer is deposited on top of older layers. This relationship is called the *principle of superposition*.

3. Sedimentary rocks form in layers that are horizontal. This relationship is...
called the principle of original horizontality. The tilting of the sedimentary rocks indicates that they have been deformed by tectonic or other forces after the sediments were deposited.

4. The walls, arches, and towers of both parks are not permanent features; they are actively changing through both weathering and erosion.

5. Much of the sandstone in both parks formed from lithification of windblown sand dunes. The processes that form cross-bedding in the sandstone are explained under “Physical Sedimentary Structures” earlier in this chapter.

Follow-Up Questions

1. Explain how sedimentary rock layers can violate the principle of superposition (i.e., how the older layers can be stacked above younger layers.) Consult “Relative Geologic Time” in Chapter 4.

2. Describe two or three different structures that might be found in beach sediment. Consult “Physical Sedimentary Structures” in this chapter.

3. What kinds of information would a geologist use to correlate sandstone layers found in Utah to layers found in Arizona? Consult Section 4-4 (“Unconformities and Correlation”) in Chapter 4.

What to See When You Go

You can take this trip for its scenic beauty and to learn about the geology of these National parks before reading further in this book. However, your understanding of the geology will be greatly enhanced if you read the sections of Chapter 3, Chapter 4, and Chapter 10 noted here before taking the trip or as you travel through Arches and Capitol Reef National Parks on the field trip.

As you follow the field trip, notice that the sedimentary rocks show conspicuous layering, also called “bedding,” and that there is clear evidence that the towers, cliffs, and arches are crumbling away due to weathering and erosion.
As you learned under “Physical Sedimentary Structures” in this chapter, sandstone consists of lithified sand grains. Here you can see how the sand grains formed asymmetric ripples as the sand was deposited by flowing water.
The “Physical Sedimentary Structures” topic in this chapter also explains that mud cracks in shale form when wet sediment deposited in water dries and shrinks. Thus, when these mud cracks formed, the land surface was occasionally inundated by shallow water and periodically exposed to air.
Metamorphism commonly alters both the texture and mineral content of a rock.

Chapter 3: Rocks: 3-4c Textural Changes

3-4c Textural Changes

As a rock undergoes metamorphism, some mineral grains grow larger and others shrink. The shapes of the grains may also change. For example, the fossiliferous limestone shown in Figure 3.13 is a sedimentary rock, but if it is subject to high temperature and pressure, the small calcite crystals that make up both the fossils and the cement between them will recrystallize, with some crystals growing at the expense of others. In the process, the fossils will be slowly destroyed and the rock will transform into marble, a metamorphic rock composed of calcite but with a texture consisting instead of large, interlocking crystals.

Micas are common metamorphic minerals that form when many different parent rocks undergo metamorphism. Micas are shaped like pie plates. When metamorphism occurs without deformation—without causing the rocks to change shape—the micas grow with random orientations, like pie plates flying through the air (Figure 3.17A). However, when tectonic force squeezes rocks as they are heated during metamorphism, the rock deforms into folds. When rocks are folded as mica crystals are growing, the micas grow with their flat surfaces perpendicular to the direction of the squeezing. This parallel alignment of micas (and other minerals) produces the metamorphic layering called foliation (The layering in metamorphic rocks resulting from regional dynamothermal metamorphism.) (Figure 3.17B).

Figure 3.17

(A) When metamorphism occurs without deformation, platy micas grow with random orientations. (B) When deformation accompanies metamorphism, platy micas orient perpendicular to the force squeezing the rocks, forming foliated metamorphic rocks. The wavy lines represent original sedimentary layers that have been folded by the deformation.
The foliation layers can range in thickness from a fraction of a millimeter to a meter or more. Metamorphic rocks commonly will break parallel to foliation planes to form slaty cleavage (A metamorphic foliation producing a parallel fracture pattern that cuts across the original sedimentary bedding).

Although metamorphic foliation and the slaty cleavage that results can resemble sedimentary bedding (stratification), the two types of layering are different in origin. Foliation results from the alignment and segregation of metamorphic minerals during metamorphism; it forms at right angles to the forces acting on the rocks. Stratification develops because sediments are deposited layer by layer.

3-4d Mineralogical Changes

Sometimes, when a parent rock contains only one mineral, metamorphism transforms the rock into one composed of the same mineral but with a coarser texture. Limestone converting to marble is one example of this generalization: both rocks consist of the mineral calcite, but their respective textures are very different. Another example is the metamorphism of quartz sandstone to quartzite, a rock composed of recrystallized quartz grains.

In contrast, metamorphism of a parent rock containing several minerals usually forms a rock with new and different minerals and a new texture. For example, a typical shale contains large amounts of clay as well as quartz feldspar and several other minerals. When
heated, some of those minerals decompose, and their atoms recombine to form new minerals such as mica, garnet, and a different kind of feldspar. Figure 3.18B shows a rock called gneiss that formed when metamorphism altered both the texture and the minerals of shale. If migrating fluids alter the chemical composition of a rock, new minerals invariably form.

Figure 3.18

3.4e Types of Metamorphism and Metamorphic Rocks

Recall that rising temperature, rising pressure, and changing chemical environment cause metamorphism. In addition, deformation resulting from the movement of Earth’s crust causes foliation to develop and thus strongly affects the texture of a metamorphic rock. Four different geologic processes create these changes.

Contact Metamorphism

Contact metamorphism occurs where hot magma intrudes cooler rock of any type—sedimentary, metamorphic, or igneous. The highest grade metamorphic rocks form at the contact point, closest to the magma. Lower-grade rocks develop farther away. A metamorphic halo (The zone surrounding an intrusive igneous body in which the country rock has been metamorphosed by heat and hydrothermal fluids from the cooling magma.) around a pluton can range in width from less than a meter to hundreds of meters, depending on the size and temperature of the intrusion and the effects of water or other fluids (Figure 3.19). Contact metamorphism commonly occurs without deformation. As a result, the metamorphic minerals grow with random orientations—like the pie plates flying through the air—and the rocks develop no foliation.

Figure 3.19

A halo of contact metamorphism, shown in red, surrounds a pluton. The later
intrusion of the basalt dike (a sheetlike, intrusive rock) metamorphosed both the pluton and the existing sedimentary rock, creating a second metamorphic halo.

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**Burial Metamorphism**

Burial metamorphism results from the burial of rocks in a sedimentary basin. Younger sediment may bury the oldest layers to depths greater than 10 kilometers in a large basin. Over time, temperature and pressure increase within the deeper layers until burial metamorphism begins.

Burial metamorphism is occurring today in the sediments underlying many large deltas, including the Mississippi River delta, the Amazon Basin on the east coast of South America, and the Niger River delta on the west coast of Africa. Like contact metamorphism, burial metamorphism occurs without deformation. Consequently, metamorphic minerals grow with random orientations and, like contact metamorphic rocks, burial metamorphic rocks are unfoliated.

**Regional Dynamothermal Metamorphism**

Regional dynamothermal metamorphism occurs where major crustal movements build mountains and deform rocks. The term *dynamothermal* simply indicates that the rocks are being deformed and heated at the same time. It is the most common and widespread type of metamorphism and affects broad regions of Earth’s crust.

Magma rises and heats large portions of the crust in places where tectonic plates converge (see Chapter 6). The high temperatures cause new metamorphic minerals to form
throughout the region. The rising magma also deforms the hot, plastic country rock as it forces its way upward. At the same time, the movements of the crust squeeze and deform rocks. As a result of all these processes acting together, regionally metamorphosed rocks are strongly foliated and are typically associated with mountains and igneous rocks. Regional dynamothermal metamorphism produces zones of foliated metamorphic rocks tens to hundreds of kilometers across. For example, large portions of the Appalachian Mountains in the eastern United States have undergone dynamothermal metamorphism and exhibit well-developed foliation.

Among the best examples of the changes in texture and mineral content that accompany metamorphism are those that occur in shale with increasing metamorphic grade. The most abundant type of sedimentary rock, shale consists mainly of clay minerals, quartz, and feldspar. The mineral grains are too small to be seen with the unaided eye. As regional metamorphism begins, clay minerals break down and mica and chlorite replace them. These new, platy minerals grow perpendicular to the direction of squeezing. As a result, the rock develops slaty cleavage and is called slate. With rising temperature and continued deformation, the micas and chlorite grow larger, and wavy or wrinkled surfaces replace the flat slaty cleavage, creating phyllite—which has a glossy appearance compared to slate, which is more dull. In both slate and phyllite, the mica and chlorite are too small to be seen with the unaided eye.

As the temperature continues to rise, the mica and chlorite grow large enough to be seen without a microscope and foliation becomes very well developed. Rock of this type is called schist. Schist forms approximately at the transition from low to intermediate metamorphic grades.

At high metamorphic grades, light- and dark-colored minerals often separate into bands that are thicker than the layers of schist, to form a rock called gneiss (pronounced “nice”). At the highest metamorphic grade, the rock begins to melt, though only partially, forming small veins of granitic magma. When metamorphism wanes and the rock cools, the magma veins solidify to form migmatite, a mixture of igneous and metamorphic rock.

**Figure 3.20**

As shale is metamorphosed, it undergoes changes in texture and mineral content. Low-grade metamorphism changes shale to slate, a dull, finely crystalline rock that is harder than shale. With increased metamorphism slate transforms to phyllite, a rock characterized by shiny, foliated surfaces such as those seen here. Schist forms at a higher metamorphic grade and has crystals big enough to see with the unaided eye. Gneiss, a high-grade metamorphic rock, is coarsely crystalline and characterized by segregated layers of lighter-colored and darker-colored minerals. Migmatite forms by partial melting of a gneiss and typically shows well-developed folds formed when the rock was plastic.
Hydrothermal Metamorphism

Water is a chemically active fluid; it attacks and dissolves rocks and minerals. If the water is hot, it attacks minerals even more rapidly. Hydrothermal metamorphism (also called hydrothermal alteration or metasomatism) occurs when hot water and ions dissolved in the hot water react with a rock to change its chemical composition and minerals.

Most rocks and magma contain very low concentrations of metals such as gold, silver, copper, lead, and zinc. For example, gold makes up 0.000002 percent of average crustal rock, while copper makes up 0.0058 percent and lead comprises 0.0001 percent. Although the metals are present in very low concentrations, hydrothermal solutions sweep slowly through large volumes of country rock, dissolving and accumulating the metals as they go. The solutions then deposit the dissolved metals where they encounter changes in temperature, pressure, or chemical environment (Figure 3.21). In this way, hydrothermal solutions scavenge and concentrate metals from average crustal rocks and then deposit them locally to form ore. Hydrothermal ore deposits are discussed further in Chapter 5.

Figure 3.21

Hydrothermal ore deposits form when hot water dissolves metals from country rock and deposits them in fractures and surrounding country rock.
### Common Igneous Rocks

<table>
<thead>
<tr>
<th>Felsic</th>
<th>Intermediate</th>
<th>Mafic</th>
<th>Ultramafic</th>
</tr>
</thead>
<tbody>
<tr>
<td>obsidian</td>
<td>andesite</td>
<td>basalt</td>
<td>peridotite</td>
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<tr>
<td>granite</td>
<td>diorite</td>
<td>gabbro</td>
<td></td>
</tr>
<tr>
<td>rhyolite</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Common Sedimentary Rocks

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<th>Bioclastic</th>
<th>Organic</th>
<th>Chemical</th>
</tr>
</thead>
<tbody>
<tr>
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<td>limestone</td>
<td>chert</td>
<td>evaporite</td>
</tr>
<tr>
<td>sandstone</td>
<td>some dolomite</td>
<td>coal</td>
<td>some dolomite (dolostone)</td>
</tr>
<tr>
<td>siltstone</td>
<td>coquina</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Common Metamorphic Rocks

<table>
<thead>
<tr>
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<th>Foliated</th>
</tr>
</thead>
<tbody>
<tr>
<td>marble</td>
<td>slate</td>
</tr>
<tr>
<td>quartzite</td>
<td>phyllite</td>
</tr>
<tr>
<td>schist</td>
<td></td>
</tr>
<tr>
<td>gneiss</td>
<td></td>
</tr>
<tr>
<td>migmatite</td>
<td></td>
</tr>
</tbody>
</table>

Chapter Review

Key Terms

- **basement rock** (The older igneous and metamorphic rock that lies beneath the thin layer of sedimentary rocks and soil covering much of Earth’s surface; forms the “basement” of the crust.)

- **bedding** (Layering that develops as sediments are deposited; also called *stratification*.)

- **bedrock** (The solid rock that lies beneath soil or unconsolidated sediments; it can be igneous, metamorphic, or sedimentary.)

- **biogenic structures** (Any physical trace left in the sedimentary record by a fossil organism; includes tracks, trails, burrows, and root casts.)

- **carbonate rocks** (Bioclastic sedimentary rocks composed of the carbonate minerals (minerals based on the $\text{CO}_3^{2-}$-anion).)

Chapter 3: Rocks Chapter Review

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- **chalk** (A very fine-grained limestone made up of the remains of tiny marine microorganisms.)

- **compaction** (Increased packing together of sedimentary grains, usually resulting from the weight of overlying sediment; causes a decrease in porosity and contributes to lithification.)

- **conglomerate** (A clastic sedimentary rock that consists of lithified gravel.)

- **coquina** (A limestone made up entirely of shell fragments.)

- **country rock** (The older rock already in an area, cut into by a younger igneous intrusion or mineral deposit.)

- **cross-bedding** (A sedimentary structure in which wind or water deposits sets of beds that are inclined to the main sedimentary layering.)

- **extrusive igneous rock** (Igneous rock formed from material that has erupted through the crust onto the surface of Earth; usually finely crystalline. Also called *volcanic rock*.)

- **foliation** (The layering in metamorphic rocks resulting from regional dynamothermal metamorphism.)

- **fossils** (The imprint, remains, or any other trace of a plant or animal preserved in rock.)

- **igneous rock** (Rock that forms when magma cools and crystallizes.)

- **intrusive igneous rock** (A rock formed when magma solidifies within Earth’s crust without erupting to the surface; usually medium to coarsely crystalline. Also called *plutonic rock*.)

- **lava** (Fluid magma that flows onto Earth’s surface from a volcano or fissure. Also, the rock formed by solidification of the same fluid magma.)

- **lithification** (The process by which loose sediment is converted to solid rock.)

- **magma** (Molten rock generated from melting of any rock in the subsurface; cools to form igneous rock.)

- **metamorphic grade** (The intensity of metamorphism that formed a rock; the maximum temperature and pressure attained during metamorphism.)

- **metamorphic halo** (The zone surrounding an intrusive igneous body in which the country rock has been metamorphosed by heat and hydrothermal fluids from the cooling magma.)

- **metamorphic rock** (A rock formed when igneous, sedimentary, or other metamorphic rocks recrystallize in response to elevated temperature, increased...
pressure, chemical change, and/or deformation.)

- **metamorphism** (The process by which rocks change texture and mineral content in response to variations in temperature, pressure, chemical conditions, and/or deformation.)

- **mud cracks** (Irregular polygonal downward-tapering fractures that develop when mud dries; may be preserved when the mud is lithified.)

- **parent rock** (Any original rock before it is changed by weathering, metamorphism, or other geological processes.)

- **peat** (A loose, unconsolidated, brownish mass of partially decayed plant matter; a precursor to coal.)

- **pore space** (The empty space between particles of rock, sediment, or soil.)

- **precipitation** (A chemical reaction that produces a solid salt, called a precipitate, from a liquid solution.)

- **ripple marks** (Small, semiparallel ridges and troughs formed mostly in sand by wind, water currents, or waves; often preserved when the sediment is lithified.)

- **rock cycle** (The sequence of events in which rocks are formed, destroyed, altered, and reformed by geological processes.)

- **sediment** (Solid rock or mineral fragments that are transported and deposited by wind, water, gravity, or ice; that are weathered by natural forces, precipitated by chemical reactions, or secreted by organisms; and that accumulate in loose, unconsolidated layers.)

- **sedimentary rock** (Rock formed when sediment becomes compacted and cemented through the process of lithification.)

- **sedimentary structures** (Any feature of sedimentary rock formed by physical processes during or shortly after deposition; examples include stratification, cross-bedding, ripple marks, and tool marks.)

- **shale** (A clastic sedimentary rock that consists of lithified clay minerals and minor amounts of silt-sized quartz, feldspar, other minerals, and organic particles. The organic material in shale is the source of most oil and natural gas.)

- **slaty cleavage** (A metamorphic foliation producing a parallel fracture pattern that cuts across the original sedimentary bedding.)

- **texture** (The size, shape, and arrangement of mineral grains, or crystals, in a rock.)

- **weathering** (The decomposition and disintegration of rocks and minerals at Earth's surface by chemical and physical processes.)
Chapter Review

Chapter Review

3-1

Rocks and the Rock Cycle

Geologists divide rocks into three groups, depending upon how the rocks formed. Igneous rocks solidify from magma. Sedimentary rocks form from clay, sand, gravel, and other sediment that collects at Earth's surface. Metamorphic rocks form when any rock is altered by temperature, pressure, or an influx of hot water. The rock cycle summarizes processes by which rocks continuously recycle in the outer layers of Earth, forming new rocks from old ones. Rock cycle processes exchange energy and materials with the atmosphere, the hydrosphere, and the biosphere.

Figure 3.1

The rock cycle shows that rocks change over geologic time. The arrows show paths that rocks can follow as they change.
Igneous Rocks

Extrusive (or volcanic) igneous rocks are fine-grained rocks that solidify from magma that has erupted onto Earth’s surface. Granite and basalt are the two most common igneous rocks. Intrusive (or plutonic) igneous rocks are medium- to coarse-grained rocks that solidify within Earth’s crust.

Sedimentary Rocks

Sediment forms by the weathering of rocks and minerals. It includes all solid particles such as rock and mineral fragments, organic remains, and precipitated minerals. It is transported by streams, glaciers, wind, and gravity; is deposited in layers; and eventually is lithified to form sedimentary
rock. Shale, sandstone, and limestone are the most common kinds of sedimentary rock.

**Figure 3.5**

Earth’s sedimentary rocks: Shale, siltstone, and sandstone are clastic rocks that make up about 85 percent of all sedimentary rocks. Limestone and other sedimentary rocks make up less than 15 percent.

---

**Metamorphic Rocks**

When a rock is heated, when pressure increases, or when hot water alters its chemistry, both its minerals and its textures change in a process called metamorphism. Contact metamorphism affects rocks heated by a nearby igneous intrusion. Burial metamorphism alters rocks as they are buried deeply within Earth’s crust. In regions where tectonic plates converge, high temperature, deformation from rising magma, and plate movement all combine to cause regional dynamothermal metamorphism. Hydrothermal metamorphism is caused by hot solutions soaking through rocks and is often associated with emplacement of ore deposits. Slate, schist, gneiss, and marble are common metamorphic rocks.
Review Questions

1. Explain what the rock cycle tells us about Earth processes.

2. Describe ways in which rock cycle processes exchange energy and materials with the atmosphere, the hydrosphere, and the biosphere.

3. What are the three main kinds of rock in Earth’s crust?

4. How do the three main types of rock differ from each other?

5. What is magma? Where does it originate?

6. Describe how igneous rocks are classified and named.

7. What are the two most common kinds of igneous rock?

8. Describe and explain the differences between plutonic and volcanic rock.

9. What is sediment? How does it form?

10. How do sedimentary grains become rounded?

11. Where in your own area would you look for rounded sediment?

12. Describe how sediment becomes lithified.

13. What are the differences among shale, sandstone, and limestone?

14. Explain why almost all sedimentary rocks are layered, or bedded.

15. How does cross-bedding form?

16. What is metamorphism? What factors cause metamorphism?

17. What kinds of changes occur in a rock as it is metamorphosed?

18. What is metamorphic foliation? How does it differ from sedimentary bedding?

19. How do contact metamorphism and regional metamorphism differ, and how are they similar?