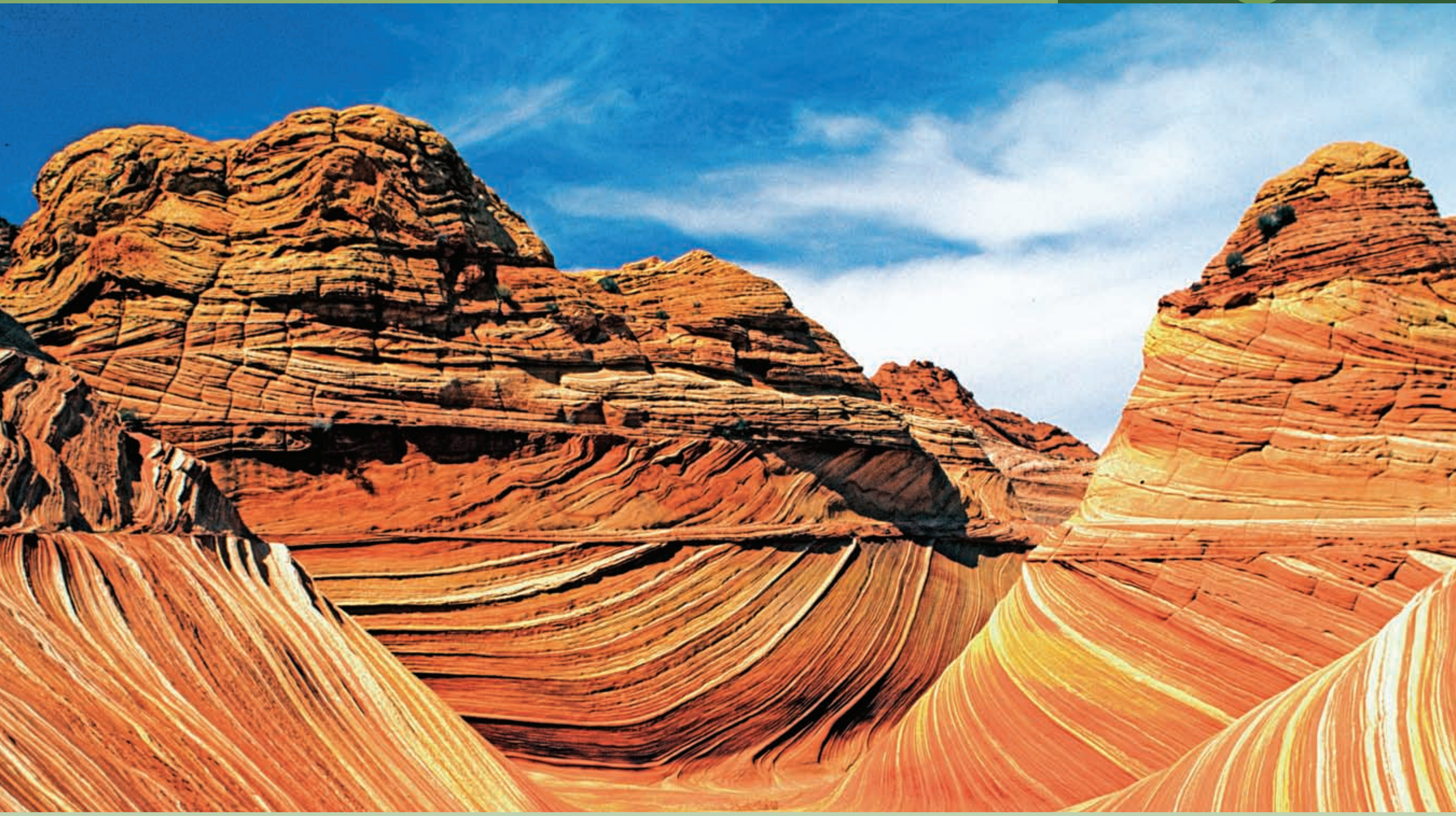
CHAPTER 6

Sediment and Sedimentary Rocks



Eroded sandstone formations formed from ancient sand dunes, North Coyote Buttes, Arizona. *Photo © Doug Sherman/Geofile*

LEARNING OBJECTIVES

- Know why sedimentary rocks are important to geologists and valuable in general.
- Using the rock cycle, explain how sediment is formed and may become a sedimentary rock.
- Describe how the three main types of sedimentary rocks are classified.
- Define *detrital sediment* and know how detrital sedimentary rocks are classified and identified.
- Explain how chemical sedimentary rocks are formed, and give several examples.
- Describe how coal forms and explain the origin of oil and gas.
- Illustrate how sedimentary structures identify how sediment was transported and used to interpret the environment of deposition.
- Describe what clues a geologist uses to interpret where and how a sedimentary rock formed and why this is important.

The rock cycle is a conceptual model of the constant recycling of rocks as they form, are destroyed, and then reform (figure 6.1). We began our discussion of the rock cycle with igneous rock (chapters 3 and 4), and we now discuss sedimentary rocks. In this chapter, we first describe sediment and sedimentary rock and then discuss sedimentary structures and fossils. We also consider the importance of sedimentary rocks for interpreting the history of Earth and their tremendous economic importance. Metamorphic rocks, the third major rock type, are the subject of chapter 7.

You saw in chapter 5 how weathering produces sediment. In this chapter, we explain more about sediment origin, as well as the erosion, transportation, sorting, deposition, and eventual transformation of sediments to sedimentary rock. Because they have such diverse origins, sedimentary rocks are difficult to classify. We divide them into detrital, chemical, and organic sedimentary rocks, but this classification does not do justice to the great variety of sedimentary rock types. Furthermore, despite their great variety, only three sedimentary rocks are very common—shale, sandstone, and limestone.

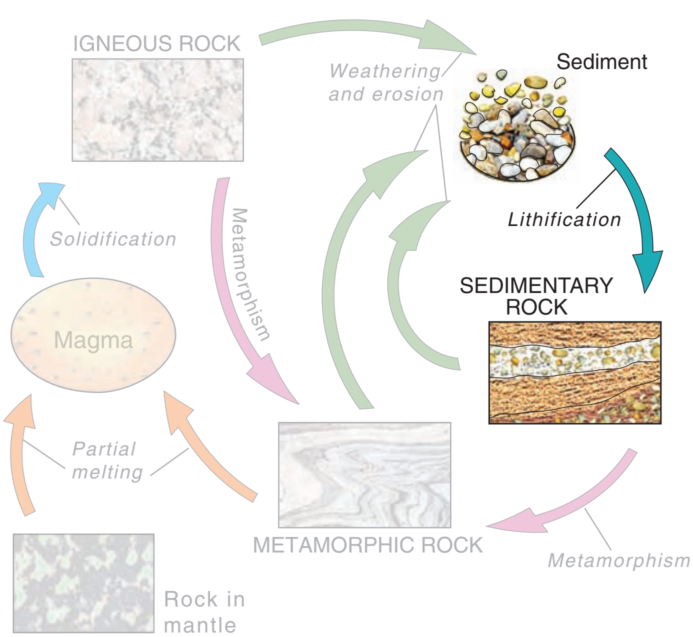


FIGURE 6.1

The rock cycle shows how rocks can be weathered and eroded and recycled into sediment to form new rocks.

Sedimentary rocks contain sedimentary structures such as ripple marks, cross-beds, and mud cracks, as well as the fossilized remains of extinct organisms. These features, combined with knowledge of the sediment types within the rock and the sequence of rock layers, give geologists clues to interpret the environments in which the rocks were deposited. About three-fourths of the surface of the continents is blanketed by sedimentary rock, providing geologists with the information they need to reconstruct a detailed history of the surface of Earth and its biosphere.

Sedimentary rocks are also economically important. Most building materials such as stone, concrete, silica (glass), gypsum (plaster), and iron are quarried and mined from sedimentary rock (see box 6.1). Salt is also a sedimentary product and, in many places in the world, supplies of fresh water are pumped from sedimentary layers. Coal, crude oil, and natural gas, the fossil fuels that drove the Industrial Revolution, are all formed within and extracted from sedimentary rock.

SEDIMENT

Most sedimentary rocks form from loose grains of sediment. **Sediment** is the collective name for loose, solid particles of mineral that originate from:

1. Weathering and erosion of preexisting rocks (detrital sediments).
2. Precipitation from solution, including secretion by organisms in water (chemical sediments).

Sediment includes such particles as sand on beaches, mud on a lake bottom, boulders frozen into glaciers, pebbles in streams, and dust particles settling out of the air. An accumulation of clam shells on the sea bottom offshore is sediment, as are coral fragments broken from a reef by large storm waves.

These particles usually collect in layers on Earth's surface. An important part of the definition is that the particles are loose. Sediments are said to be *unconsolidated,* which means that the grains are separate, or unattached to one another.

Detrital sediment particles are classified and defined according to the size of individual fragments. Table 6.1 shows the precise definitions of particles by size.

Gravel includes all rounded particles coarser than 2 millimeters in diameter, the thickness of a U.S. nickel. (Angular fragments of this size are called *rubble.*) *Pebbles* range from 2 to 64 millimeters (about the size of a tennis ball). *Cobbles* range from 64 to 256 millimeters (about the size of a basketball), and *boulders* are coarser than 256 millimeters (figure 6.2).

Sand grains are from 1/16 millimeter (about the thickness of a human hair) to 2 millimeters in diameter. Grains of this size are visible and feel gritty between the fingers. **Silt** grains are from 1/256 to 1/16 millimeter. They are too small to see without a magnifying device, such as a geologist's hand lens. Silt does not feel gritty between the fingers, but it does feel gritty between the teeth (geologists commonly bite sediments to test their grain size). **Clay** is the finest sediment, at less than 1/256 millimeter, too fine to feel gritty to fingers or teeth. *Mud* is a term loosely used for a mixture of silt and clay.

Note that we have two different uses of the word *clay*—a *clay-sized particle* (table 6.1) and a *clay mineral.* A clay-sized particle can be composed of any mineral at all provided its diameter is less than 1/256 millimeter. A clay mineral, on the other hand, is one of a small group of silicate minerals with a sheet-silicate structure. Clay minerals usually form in the clay-size range.

Quite often the composition of sediment in the clay-size range turns out to be mostly clay minerals, but this is not always the case. Because of its resistance to chemical weathering, quartz may show up in this fine-size grade. (Most silt is quartz.) Intense mechanical weathering can break down a wide variety of minerals to clay size, and these extremely fine particles may retain their mineral identity for a long time if chemical weathering is slow. The great weight of glaciers is particularly effective at grinding minerals down to the silt- and clay-size range, producing "rock flour," which gives a milky appearance to glacial meltwater streams (see chapter 12).

Weathering, erosion, and transportation are some of the processes that affect the character of sediment. Both mechanically weathered and chemically weathered rock and sediment can be eroded, and weathering continues as erosion takes place.

TABLE 6.1 Sediment Particles and Detrital Sedimentary Rocks

Diameter (mm)	Sediment		Sedimentary Rock
256	Boulder	Gravel	**Breccia** (angular particles) or **conglomerate** (rounded particles)
64	Cobble		
	Pebble		
2	Sand		**Sandstone**
1/16	Silt	"Mud"	Siltstone (mostly silt)
1/256	Clay		**Shale** or mudstone (mostly clay)

Sandstone and shale are quite common; the others are relatively rare.

FIGURE 6.2

These boulders have been rounded by abrasion as wave action rolled them against one another on this beach. *Photo by David McGeary*

Sand being transported by a river also can be actively weathered, as can mud on a lake bottom. The character of sediment can also be altered by *rounding* and *sorting* during transportation, and even after eventual *deposition.*

Transportation

Most sediment is **transported** some distance by gravity, wind, water, or ice before coming to rest and settling into layers. During transportation, sediment continues to weather and change in character in proportion to the distance the sediment is moved.

Rounding is the grinding away of sharp edges and corners of rock fragments during transportation. Rounding occurs in sand and gravel as rivers, glaciers, or waves cause particles to hit and scrape against one another (figure 6.2) or against a rock surface, such as a rocky streambed. Boulders in a stream may show substantial rounding in less than 1 kilometer of travel.

Sorting is the process by which sediment grains are selected and separated according to grain size (or grain shape or specific gravity) by the agents of transportation, especially by running water. Because of their high viscosity and manner of flow, glaciers are poor sorting agents. Glaciers deposit all sediment sizes in the same place, so glacial sediment usually consists of a mixture of clay, silt, sand, and gravel. Such glacial sediment is considered *poorly sorted.* Sediment is considered *well-sorted* when the grains are nearly all the same size. A river, for example, is a good sorting agent, separating sand from gravel, and silt and clay from sand. Sorting takes place because of the greater weight of larger particles. Boulders weigh more than pebbles and are more difficult for the river to transport, so a river must flow more rapidly to move boulders than to move pebbles. Similarly, pebbles are harder to move than sand, and sand is harder to move than silt and clay.

Figure 6.3 shows the sorting of sediment by a river as it flows out of steep mountains onto a gentle flood plain, where the water loses energy and slows down. As the river loses

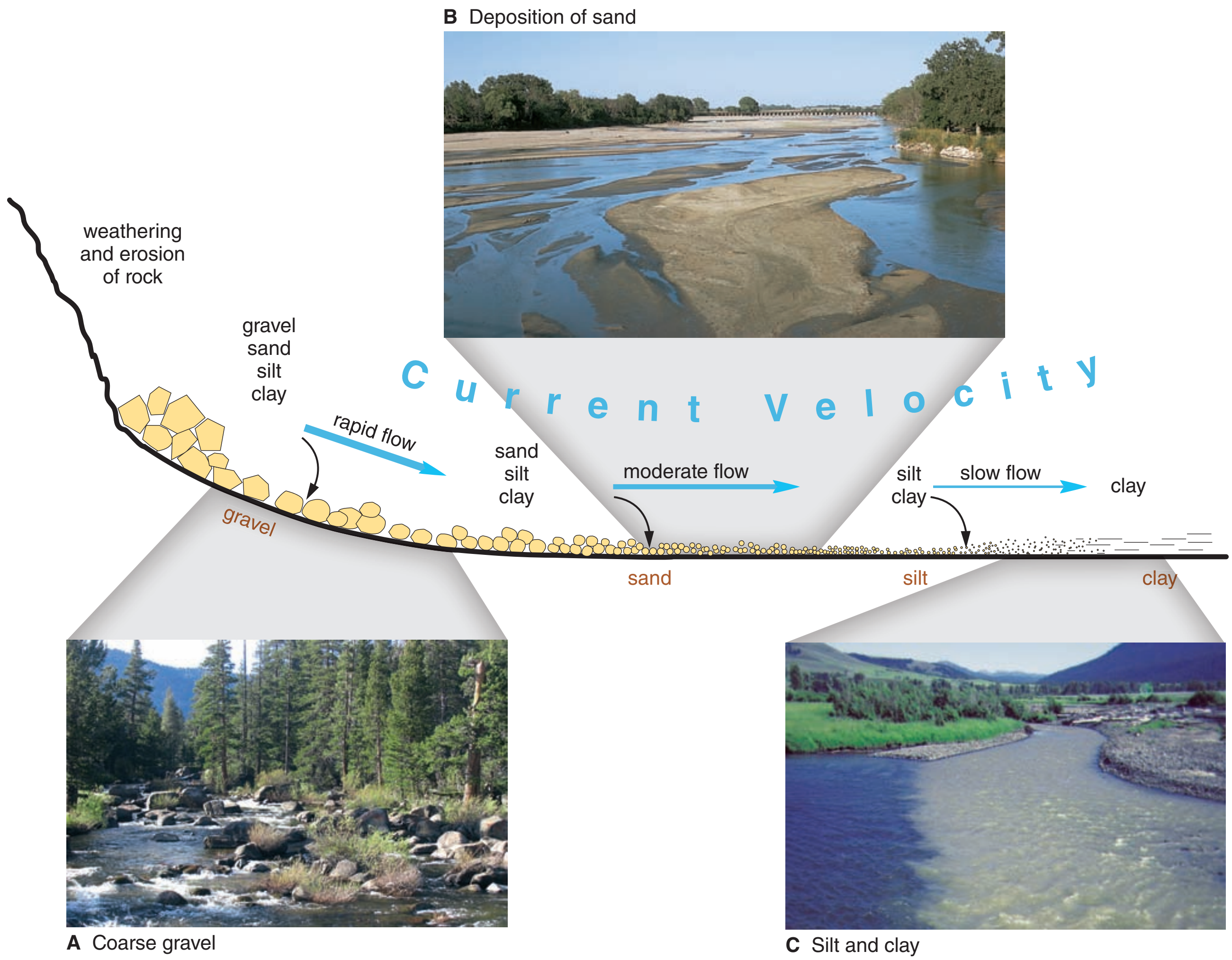


FIGURE 6.3

Cross-sectional (profile) view of sorting sediment by a river. (*A*) The coarsest material (gravel) is deposited first in the headwaters of the river where the flow of water is rapid. (*B*) Deposition of sand occurs as the river loses energy as it flows across a floodplain. (*C*) Silt and clay are carried and eventually deposited at the mouth of a river when the current velocity slows. *Photo A by Diane Carlson; Photo B by Dave McGeary; Photo C by C. W. Montgomery*

energy, the heaviest particles of sediment are deposited. The boulders come to rest first (figure 6.3*A*). As the river continues to slow and becomes less turbulent, cobbles and then pebbles are deposited. Sand comes to rest as the river loses still more energy (figure 6.3*B*). Finally, the river is carrying only the finest sediment—silt and clay (figure 6.3*C*). The river has sorted the original sediment mix by grain size.

Deposition

When transported material settles or comes to rest, **deposition** occurs. Sediment is deposited when running water, glacial ice, waves, or wind loses energy and can no longer transport its load.

Deposition also refers to the accumulation of chemical or organic sediment, such as clam shells on the sea floor or plant material on the floor of a swamp. Such sediments may form as organisms die and their remains accumulate, perhaps with no transportation at all. Deposition of salt crystals can take place as seawater evaporates. A change in the temperature, pressure, or chemistry of a solution may also cause precipitation—hot springs may deposit calcite or silica as the warm water cools.

The **environment of deposition** is the location in which deposition occurs. A few examples of environments of deposition are the deep-sea floor, a desert valley, a river channel, a coral reef, a lake bottom, a beach, and a sand dune. Each environment is marked by characteristic physical, chemical, and biological conditions. You might expect mud on the sea floor to differ from mud on a lake bottom. Sand on a beach may differ from sand in a river channel. Some differences are due to varying sediment sources and transporting agents, but most are the result of conditions in the environments of deposition themselves.

One of the most important jobs of geologists studying sedimentary rocks is to try to determine the ancient environment of deposition. Geologists compare features found in modern environments of deposition with clues left in the rock record to interpret where the sedimentary rock may have formed. Such clues include the vertical sequence of rock layers in the field, the fossils and sedimentary structures found within the rock, the mineral composition of the rock, and the size, shape, and surface texture of the individual sediment grains. Later in this chapter, we give a few examples of interpreting environments of deposition.

Preservation

Not all sediments are preserved as sedimentary layers. Gravel in a river may be deposited when a river is low but then may be eroded and transported by the next flood on the river. Many sediments on land, particularly those well above sea level, are easily eroded and carried away, so they are not commonly preserved. Sediments on the sea floor are easier to preserve. In general, continental and marine sediments are most likely to be preserved if they are deposited in a *subsiding* (sinking) *basin* and if they are covered or *buried by later sediments.*

Lithification

Lithification is the general term for the processes that convert loose sediment into sedimentary rock. Most sedimentary rocks are lithified by a combination of *compaction,* which packs loose sediment grains tightly together, and *cementation,* in which the precipitation of cement around sediment grains binds them into a firm, coherent rock. *Crystallization* of minerals from solution, without passing through the loose-sediment stage, is another way that rocks may be lithified. Some layers of sediment persist for tens of millions of years without becoming fully lithified. Usually, layers of *partially lithified sediment* have been buried deep enough to become compacted but have not experienced the conditions required for cementation.

As sediment grains settle slowly in a quiet environment such as a lake bottom, they form an arrangement with a great deal of open space between the grains (figure 6.4*A*). The open spaces between grains are called *pores,* and in a quiet environment, a deposit of sand may have 40% to 50% of its volume as open **pore space**. (If the grains were traveling rapidly and impacting one another just before deposition, the percentage of pore space will be less.) As more and more sediment grains are deposited on top of the original grains, the increasing weight of this *overburden* compresses the original grains closer together, reducing the amount of pore space. This shift to a tighter packing, with a resulting decrease in pore space, is called **compaction** (figure 6.4*B*). As pore space decreases, some of the interstitial water that usually fills sediment pores is driven out of the sediment.

As underground water moves through the remaining pore space, solid material called **cement** can precipitate in the pore space and bind the loose sediment grains together to form a solid rock. The cement attaches very tightly to the grains, holding them in a rigid framework. As cement partially or completely fills the pores, the total amount of pore space is further reduced (figure 6.4*C*), and the loose sand forms a hard, coherent sandstone by **cementation**.

Sedimentary rock cement is often composed of the mineral calcite or of other carbonate minerals. Dissolved calcium and bicarbonate ions are common in surface and underground waters. If the chemical conditions are right, these ions may recombine to form solid calcite, as shown in the following reaction.

$$\underbrace{Ca^{++} + 2HCO_3^{-}}_{\text{dissolved ions}} \rightarrow \underbrace{CaCO_3}_{\text{calcite}} + H_2O + CO_2$$

Silica is another common cement. Iron oxides and clay minerals can also act as cement but are less common than calcite and silica. The dissolved ions that precipitate as cement originate from the chemical weathering of minerals such as feldspar and

FIGURE 6.4

Lithification of sand grains to become sandstone. (*A*) Loose sand grains are deposited with open pore space between the grains. (*B*) The weight of overburden compacts the sand into a tighter arrangement, reducing pore space. (*C*) Precipitation of cement in the pores by groundwater binds the sand into the rock sandstone, which has a clastic texture.

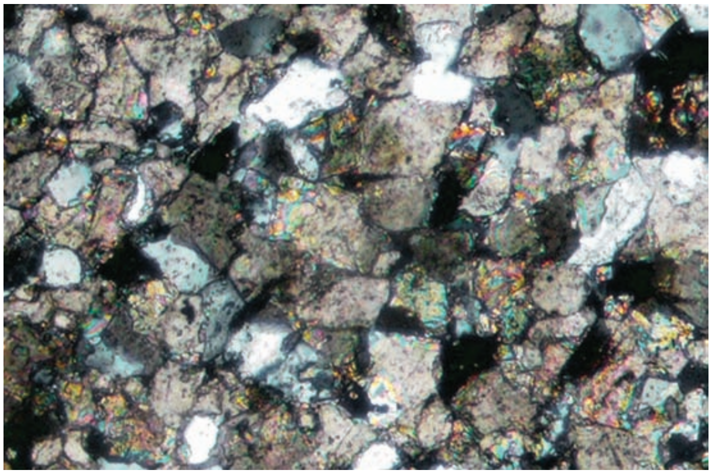


FIGURE 6.5

Crystalline dolostone as seen through a polarizing microscope. Note the interlocking crystals of dolomite mineral that grew as they precipitated during recrystallization. Such crystalline sedimentary textures have no cement or pore spaces. *Photo by Bret Bennington*

calcite. This weathering may occur within the sediments being cemented, or at a very distant site, with the ions being transported tens or even hundreds of kilometers by water before precipitating as solid cement.

A sedimentary rock that consists of sediment grains bound by cement into a rigid framework is said to have a **clastic texture**. Usually such a rock still has some pore space because cement rarely fills the pores completely (figure 6.4*C*).

Some sedimentary rocks form by **crystallization**, the development and growth of crystals by precipitation from solution at or near Earth's surface (the term is also used for igneous rocks that crystallize as magma cools). These rocks have a **crystalline texture**, an arrangement of interlocking crystals that develops as crystals grow and interfere with each other. Crystalline rocks lack cement. They are held together by the interlocking of crystals. Such rocks have minimal pore space because the crystals typically grow until they fill all available space. Some sedimentary rocks with a crystalline texture are the result of *recrystallization,* the growth of new crystals that form from and then destroy the original clastic grains of a rock that has been buried (figure 6.5).

TYPES OF SEDIMENTARY ROCKS

Sedimentary rocks are formed from (1) eroded mineral grains, (2) minerals precipitated from low-temperature solution, or (3) consolidation of the organic remains of plants. These different types of sedimentary rocks are called, respectively, *detrital, chemical,* and *organic* rocks.

Most sedimentary rocks are **detrital sedimentary rocks**, formed from cemented sediment grains that are fragments of preexisting rocks. The rock fragments can be either identifiable pieces of rock, such as pebbles of granite or shale, or individual mineral grains, such as sand-sized quartz and feldspar crystals loosened from rocks by weathering and erosion. Clay minerals formed by chemical weathering are also considered fragments of preexisting rocks. During transportation the grains may have been rounded and sorted. Table 6.1 shows the detrital rocks, such as conglomerate, sandstone, and shale, and how these rocks vary in grain size.

Chemical sedimentary rocks are deposited by precipitation of minerals from solution. An example of inorganic precipitation is the formation of *rock salt* as seawater evaporates. Chemical precipitation can also be caused by organisms. The sedimentary rock *limestone* is often formed from the cementation of broken pieces of seashell and fragments of calcite mineral produced by corals and algae. Such a rock is called a *bioclastic* limestone.

Not all chemical sedimentary rocks accumulate as sediment. Some limestones are crystallized as solid rock by corals and coralline algae in reefs. Chert crystallizes in solid masses within some layers of limestone. Rock salt may crystallize directly as a solid mass or it may form from the crystallization of individual salt crystals that behave as sedimentary particles until they grow large enough to interlock into solid rock.

Organic sedimentary rocks are rocks that are composed of organic carbon compounds. *Coal* is an organic rock that forms from the compression of plant remains, such as moss, leaves, twigs, roots, and tree trunks.

Appendix B describes and helps you identify the common sedimentary rocks. The standard geologic symbols for these rocks (such as dots for sandstone, and a "brick-wall" symbol for limestone) are shown in appendix F and will be used in the remainder of the book.

DETRITAL ROCKS

Detrital sedimentary rocks are formed from the weathered and eroded remains (detritus) of bedrock. Detrital rocks are also often referred to as *terrigenous clastic rocks* because they are composed of *clasts* (broken pieces) of mineral derived from the erosion of the land.

Breccia and Conglomerate

Sedimentary breccia is a coarse-grained sedimentary rock formed by the cementation of coarse, angular fragments of rubble (figure 6.6). Because grains are rounded so rapidly during transport, it is unlikely that the angular fragments within breccia have moved very far from their source (see figure 6.3). Sedimentary breccia is commonly a talus slope deposit that forms at the base of a steep rock cliff that is being mechanically weathered. Landslide deposits also might lithify into sedimentary breccia. This type of rock is not particularly common.

Conglomerate is a coarse-grained sedimentary rock formed by the cementation of rounded gravel. It can be distinguished from breccia by the definite roundness of its particles (figure 6.7). Because conglomerates are coarse-grained,

FIGURE 6.6

Breccia is characterized by coarse, angular fragments. The cement in this rock is colored by hematite. The wide black and white bars on the scale are 1 centimeter long; the small divisions are 1 millimeter. Note that most grains exceed 2 millimeters (table *6.1*). *Photo by David McGeary*

FIGURE 6.7

An outcrop of a poorly sorted conglomerate. Note the rounding of cobbles, which vary in composition and size. The cement in this rock is also colored by hematite. Long scale bar is 10 centimeters; short bars are 1 centimeter. *Photo by David McGeary*

the particles may not have traveled far; but some transport was necessary to round the particles. Angular fragments that fall from a cliff and then are carried a few kilometers by a river or pounded by waves crashing in the surf along a beach are quickly rounded. Gravel that is transported down steep submarine canyons or carried by glacial ice, however, can be transported tens or even hundreds of kilometers before deposition.

Sandstone

Sandstone is formed by the cementation of sand grains (figure 6.8). Any deposit of sand can lithify to sandstone. Rivers deposit sand in their channels, and wind piles up sand into dunes. Waves deposit sand on beaches and in shallow water. Deep-sea currents spread sand over the sea floor. As you might imagine, sandstones show a great deal of variation in mineral composition, degree of sorting, and degree of rounding.

Quartz sandstone is a sandstone in which more than 90% of the grains are quartz (figure 6.8*A*). Because quartz is resistant to chemical weathering, it tends to concentrate in sand deposits as the less-resistant minerals such as feldspar are weathered away. The quartz grains in a quartz sandstone are usually well-sorted and well-rounded because they have been transported for great distances (figure 6.9*A*). Most quartz sandstone was deposited as beach sand or dune sand.

A sandstone with more than 25% of the grains consisting of feldspar is called *arkose* (figure 6.8*B*). Because feldspar grains are preserved in the rock, the original sediment obviously did not undergo severe chemical weathering, or the feldspar would have been destroyed. Mountains of granite in a desert could be a source for such a sediment, for the rapid erosion associated with rugged terrain would allow feldspar to be mechanically weathered and eroded before it is chemically weathered (a dry climate slows chemical weathering). Most arkoses contain coarse, angular grains (figure 6.9*B*), so transportation distances were probably short. An arkose may have been deposited within an **alluvial fan**, a large, fan-shaped pile of sediment that usually forms where a stream emerges from a narrow canyon onto a flat plain at the foot of a mountain range (figure 6.10).

Sandstones may contain a substantial amount of **matrix** in the form of fine-grained silt and clay in the space between larger sand grains (figure 6.11). A matrix-rich sandstone is poorly sorted and often dark in color. It is sometimes called a "dirty sandstone."

Graywacke (pronounced "gray-wacky") is a type of sandstone in which more than 15% of the rock's volume consists of fine-grained matrix (figures 6.8*C* and 6.9*C*). Graywackes are commonly hard and dense, and they are generally dark gray or green. The sand grains may be so coated with matrix that they are difficult to see, but they typically consist of quartz, feldspar, and sand-sized fragments of other fine-grained sedimentary, volcanic, and metamorphic rocks. Most graywackes probably formed from sediment-laden turbidity currents that are deposited in deep water (see figure 6.29).

The Fine-Grained Rocks

Rocks consisting of fine-grained silt and clay are called *shale, siltstone, claystone,* and *mudstone.*

Shale is a fine-grained sedimentary rock notable for its ability to split into layers (called *fissility*). Splitting takes place along the surfaces of very thin layers (called *laminations*) within the shale (figure 6.12). Most shales contain both silt and clay (averaging about two-thirds clay-sized clay minerals and one-third silt-sized quartz) and are so fine-grained that the surface of the rock feels very smooth. The silt and clay deposits that lithify as shale accumulate on lake bottoms, at the ends of rivers in deltas, on river flood plains, and on quiet parts of the deep-ocean floor.

FIGURE 6.8

Types of sandstone. (*A*) Quartz sandstone; more than 90% of the grains are quartz. (*B*) Arkose; the grains are mostly feldspar and quartz. (*C*) Graywacke; the grains are surrounded by dark, fine-grained matrix. (Small scale divisions are 1 millimeter; most of the sand grains are about 1 millimeter in diameter.) *Photos by David McGeary*

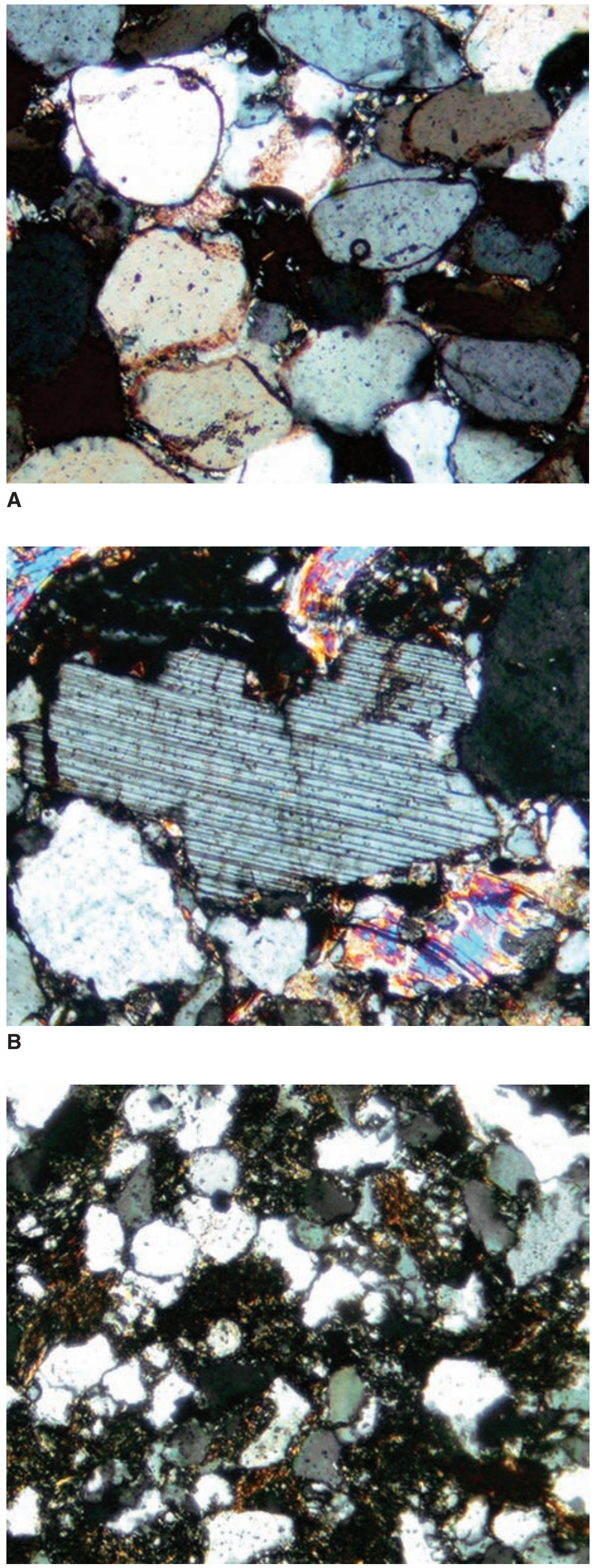


FIGURE 6.9

Detrital sedimentary rocks viewed through a polarizing microscope. (*A*) Quartz sandstone; note the well-rounded and well-sorted grains. (*B*) Arkose; large feldspar grain in center surrounded by angular quartz grains. (*C*) Graywacke; quartz grains surrounded by brownish matrix of mud. *Photos by Bret Bennington*

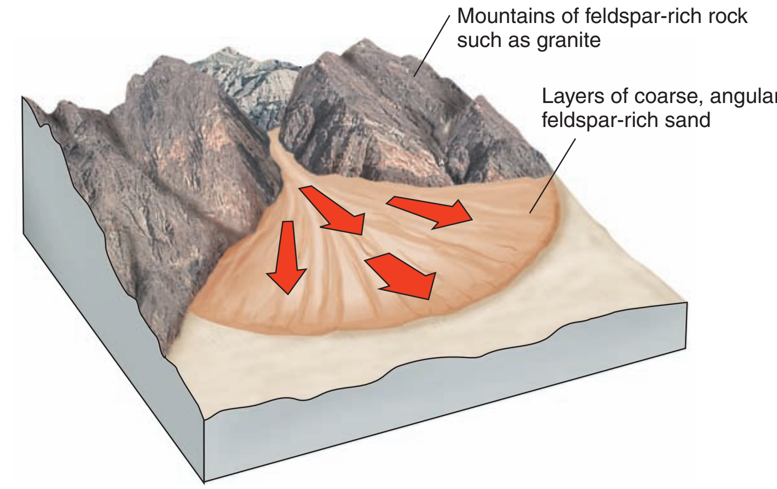


FIGURE 6.10

Feldspar-rich sand (arkose) may accumulate from the rapid erosion of feldspar-containing rock such as granite. Steep terrain accelerates erosion rates so that feldspar may be eroded before it is completely chemically weathered into clay minerals.

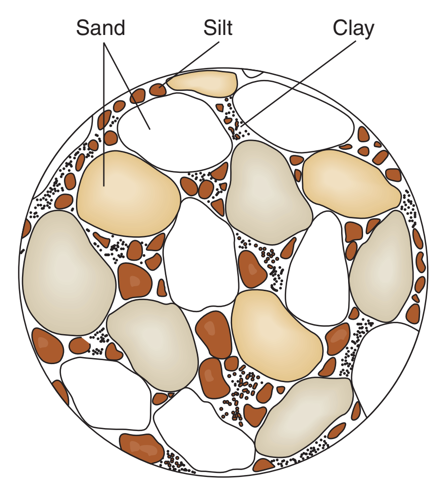


FIGURE 6.11

A poorly sorted sediment of sand grains surrounded by a matrix of silt and clay grains. Lithification of such a sediment would produce a "dirty sandstone."

Fine-grained rocks such as shale typically undergo pronounced compaction as they lithify. Figure 6.13 shows the role of compaction in the lithification of shale from wet mud. Before compaction, as much as 80% of the volume of the wet mud may have been pore space filled with water. The flake-like clay minerals were randomly arranged within the mud. Pressure from overlying material packs the sediment grains together and reduces the overall volume by squeezing water out of the pores. The clay minerals are reoriented perpendicular to the pressure, becoming parallel to one another like a deck of cards. The fissility of shale is due to weaknesses between these parallel clay flakes.

A

B

FIGURE 6.12

(*A*) An outcrop of shale from Hudson Valley in New York. Note how this fine-grained rock tends to split into very thin layers. (*B*) Shale pieces; note the very fine grain (scale in centimeters), very thin layers (laminations) on the edge of the large piece, and tendency to break into small, flat pieces (fissility). *Photo A © John Buitenkant/ Science Source; Photo B by David McGeary*

Compaction by itself does not generally lithify sediment into sedimentary rock. It does help consolidate clayey sediments by pressing the microscopic clay minerals so closely together that attractional forces at the atomic level tend to bind them together. Even in shale, however, the primary method of lithification is cementation.

A rock consisting mostly of silt grains is called *siltstone.* Somewhat coarser-grained than most shales, siltstones lack the fissility and laminations of shale. *Claystone* is a rock composed predominately of clay-sized particles but lacking the fissility of shale. *Mudstone* contains both silt and clay, having the same grain size and smooth feel of shale but lacking shale's laminations and fissility. Mudstone is massive and blocky, while shale is visibly layered and fissile.

CHEMICAL SEDIMENTARY ROCKS

Chemical sedimentary rocks are precipitated from a low-temperature aqueous environment. Chemical sedimentary rocks are precipitated either directly by inorganic processes or by the actions of organisms. Chemical rocks include *carbonates, chert,* and *evaporites.*

Carbonate Rocks

Carbonate rocks contain the CO_3^{--} ion as part of their chemical composition. The two main types of carbonates are limestone and dolomite.

Limestone

Limestone is a sedimentary rock composed mostly of calcite ($CaCO_3$). Limestones are precipitated either by the actions of organisms or directly as the result of inorganic processes. Thus, the two major types of limestone can be classified as either *biochemical* or *inorganic limestone.*

Biochemical limestones are precipitated through the actions of organisms. Most biochemical limestones are formed on continental shelves in warm, shallow seawater. Biochemical limestone may be precipitated directly in the core of a reef

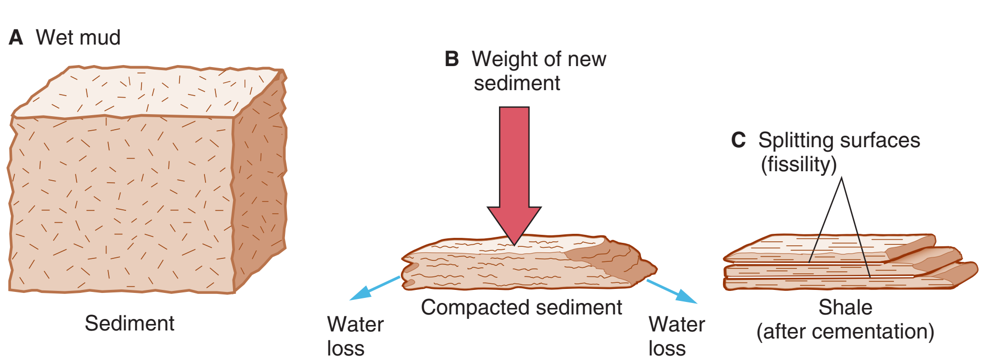


FIGURE 6.13

Lithification of shale from the compaction and cementation of wet mud. (*A*) Randomly oriented silt and clay particles in wet mud. (*B*) Particles reorient, water is lost, and pore space decreases during compaction caused by the weight of new sediment deposited on top of the wet mud. (*C*) Splitting surfaces in cemented shale form parallel to the oriented mineral grains.

by corals, encrusting algae, or other shell-forming organisms (figure 6.14). Such a rock would contain the fossil remains of organisms preserved in growth position.

Biochemical limestones may also form from wave-broken fragments of algae, corals, and shells. The fragments may be of any size (gravel, sand, silt, and clay) and are commonly sorted and rounded as they are transported by waves and currents across the sea floor (figure 6.15). The action of these waves and currents and subsequent cementation of these fragments into rock give these limestones a clastic texture. These *bioclastic* (or *skeletal*) *limestones* have a variety of appearances. They may be relatively coarse-grained with recognizable fossils (figure 6.16) or uniformly fine-grained and dense from the accumulation of microscopic fragments of calcareous algae (figures 6.16 and 6.17). A variety of limestone called *coquina* forms from the cementation of shells and shell fragments that accumulated on the shallow sea floor near shore (figure 6.18). It has a clastic texture and is usually coarse-grained, with easily recognizable shells and shell fragments in it. *Chalk* is a light-colored, porous, very fine-grained variety of bioclastic limestone that forms from the seafloor accumulation of microscopic marine organisms that drift near the sea surface (figure 6.19).

Inorganic limestones are precipitated directly as the result of inorganic processes. *Oölitic limestone* is a distinctive variety of inorganic limestone formed by the cementation of sand-sized *oöids,* small spheres of calcite inorganically precipitated in warm, shallow seawater (figure 6.20). Strong tidal currents roll the oölites back and forth, allowing them to maintain a nearly spherical shape as they grow. Wave action may also contribute to their shape. Oölitic limestone has a clastic texture.

Tufa and *travertine* are inorganic limestones that form from fresh water. Tufa is precipitated from solution in the water of a continental spring or lake, or from percolating groundwater. Travertine may form in caves when carbonate-rich water loses CO_2 to the cave atmosphere. Tufa and travertine both have a crystalline texture; however, tufa is generally more porous, cellular, or open than travertine, which tends to be more dense.

FIGURE 6.14

Corals precipitate calcium carbonate to form limestone in a reef. Water depth about 8 meters (25 feet), San Salvador Island, Bahamas. *Photo by David McGeary*

Limestones are particularly susceptible to **recrystallization**, the process by which new crystals, often of the same mineral composition as the original grains, develop in a rock. Calcite grains recrystallize easily, particularly in the presence of water and under the weight of overlying sediment. The new crystals that form are typically large and can be easily seen in a rock as slight reflections off their broad, flat cleavage faces. Recrystallization often destroys the original clastic texture and fossils of a rock, replacing them with a new crystalline texture. Therefore, the geologic history of such a rock can be very difficult to determine.

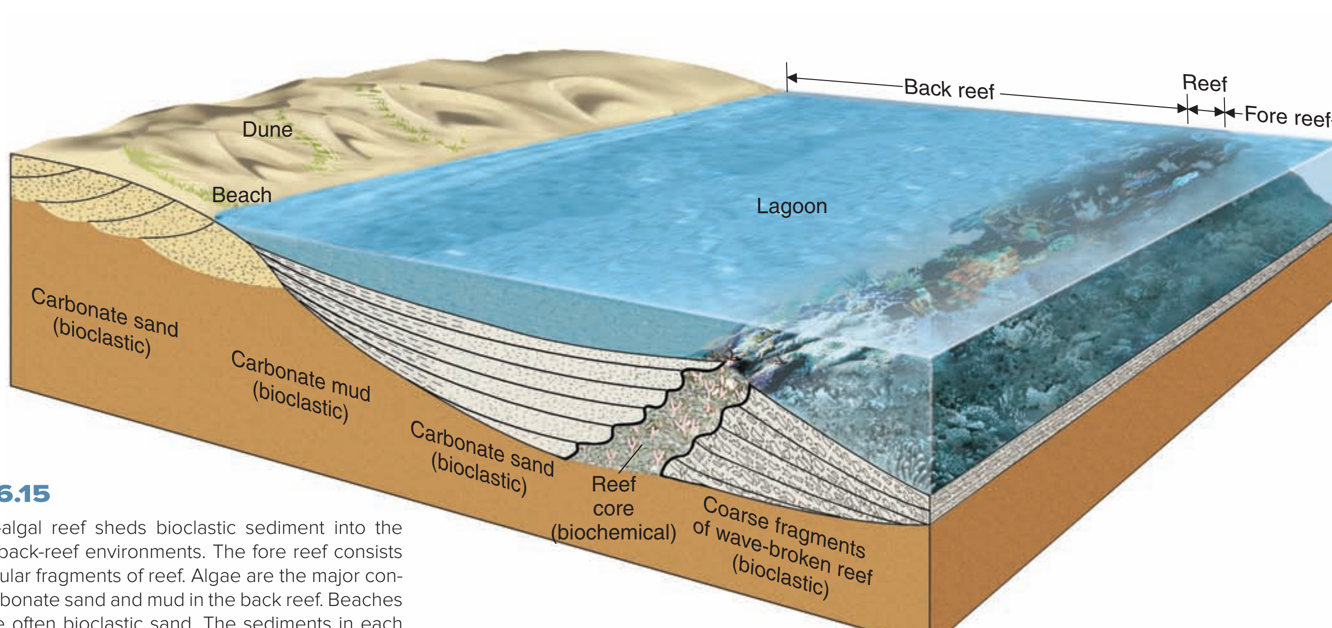


FIGURE 6.15

A living coral-algal reef sheds bioclastic sediment into the fore-reef and back-reef environments. The fore reef consists of coarse, angular fragments of reef. Algae are the major contributors of carbonate sand and mud in the back reef. Beaches and dunes are often bioclastic sand. The sediments in each environment can lithify to form highly varied limestones.

FIGURE 6.16

Bioclastic limestones. The two on the left are coarse-grained and contain visible fossils of corals and shells. The limestone on the right consists of fine-grained carbonate mud formed by calcareous algae. *Photo by David McGeary*

FIGURE 6.17

Green algae on the sea floor in 3 meters of water on the Bahama Banks. The "shaving brush" alga is *Penicillus,* which produces great quantities of fine-grained carbonate mud. *Photo by David McGeary*

FIGURE 6.18

Coquina, a variety of bioclastic limestone, is formed by the cementation of coarse shells. *Photo by David McGeary*

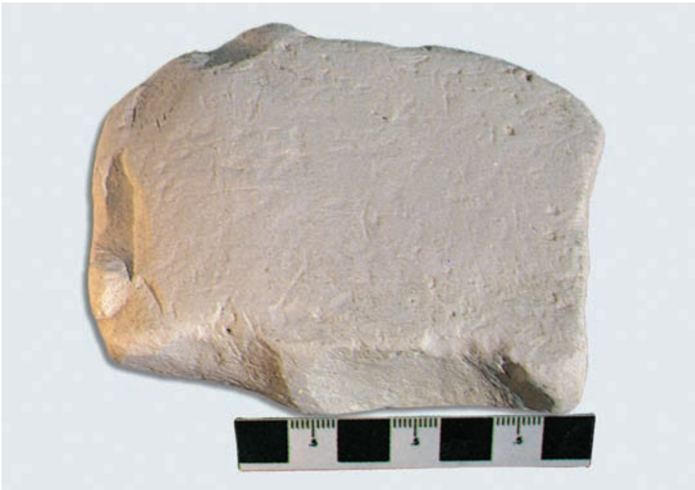


FIGURE 6.19

Chalk is a fine-grained variety of bioclastic limestone formed of the remains of microscopic marine organisms that live near the sea surface. *Photo by David McGeary*

Dolomite

The term **dolomite** (table 6.2) is used both as a rock name and as a mineral name. To avoid confusion, many geologists refer to a rock that is made mostly of the mineral dolomite as a *dolostone*. The term *dolomite* is reserved for the mineral with the chemical formula $CaMg(CO_3)_2$. Dolomite formation is important from an economic perspective, because the porosity of carbonate rocks often increases as dolomite forms. Many important oil reservoirs are in dolostone layers that have enhanced porosity from dolomite formation.

Dolomite is relatively common in the ancient rock record, but geologists have not observed significant quantities of dolomite forming in modern environments. This discrepancy

A

B

FIGURE 6.20

(*A*) Aerial photo of underwater dunes of oöids chemically precipitated from seawater on the shallow Bahama Banks, south of Bimini. Tidal currents move the dunes. (*B*) An oölitic limestone formed by the cementation of oöids (small spheres). Small divisions on scale are 1 millimeter wide. *Photos by David McGeary*

TABLE 6.2 Chemical Sedimentary Rocks

Inorganic Sedimentary Rocks			
Rock	**Composition**	**Texture**	**Origin**
Limestone	$CaCO_3$	Crystalline Oölitic	May be precipitated directly from seawater. Cementation of oölites (oöids) precipitated chemically from warm, shallow seawater (*oölitic* limestone). Also forms in caves as *travertine* and in springs, lakes, or percolating groundwater as *tufa*
Dolomite	$CaMg(CO_3)_2$	Crystalline	Alteration of limestone by Mg-rich solutions (usually)
Evaporites			Evaporation of seawater or a saline lake
Rock salt	NaCl	Crystalline	
Rock gypsum	$CaSO_4 \cdot 2H_2O$	Crystalline	
Chert	SiO_2 (silica)	Crystalline	Precipitated as nodules or layers by silica-rich groundwater
Biochemical Sedimentary Rocks			
Rock	**Composition**	**Texture**	**Origin**
Limestone	$CaCO_3$ (calcite)	Clastic or crystalline	Cementation of fragments of shells, corals, and coralline algae (*bioclastic limestone* such as coquina and chalk). Also precipitated directly by organisms in reefs
Chert	SiO_2 (silica)	Crystalline (usually)	Cementation of microscopic marine organisms; rock usually recrystallized

between ancient and modern dolomite abundance has led to what geologists refer to as the "dolomite problem." Geologists have proposed several models to explain how dolomite forms, and it is likely that dolomite forms by more than one mechanism. All models need to explain the observations that dolomite does not precipitate directly from seawater in modern environments, and that dolomite is more common in the geologic past.

Most dolomite that we see in the rock record probably forms as a replacement for existing carbonate material, and there are several models to explain the process. Studies show that although dolomite does not precipitate directly from seawater, it is common in the shallow subsurface in the Persian Gulf. In this arid region, dolomite forms in broad, flat tidal zones where the sediment is made of fine, highly reactive lime mud. The lime mud is composed of very small particles of calcite or aragonite ($CaCO_3$). Replacement reactions start when seawater evaporates from the tidal flat, leaving behind a dense, salty brine that percolates through the pore spaces of the lime mud. As the brine grows more concentrated, gypsum starts to precipitate, removing Ca ions from the pore water. The remaining pore water becomes relatively enriched in Mg, and small, poorly formed dolomite crystals begin to replace the original carbonate material. This is called "proto"-dolomite, and it forms as an early replacement for lime mud in shallow tidal flat environments. The reactions are summarized as follows:

1. Evaporation in hot, dry tidal flat environments produces salty brines that percolate through the pore spaces of the lime mud.
2. Gypsum and other evaporate minerals begin to precipitate from the dense, salty brine. This removes calcium ions from the brine.

$$Ca^{++} + SO_4^{--} + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O$$

3. The brine becomes relatively enriched in Mg^{++} ions as more gypsum precipitates. When the ratio of $Mg/Ca > 10/1$, dolomite becomes chemically stable, and Mg^{++} starts to replace Ca^{++} on an ion-by-ion basis.
4. Early, poorly crystalline "proto"-dolomite crystals form by replacement as Mg^{++} ions substitute regularly for Ca^{++} ions in the crystal structure.

$$Mg^{++} + 2CaCO_3 \rightarrow (CaMgCO_3)_2 + Ca^{++}$$

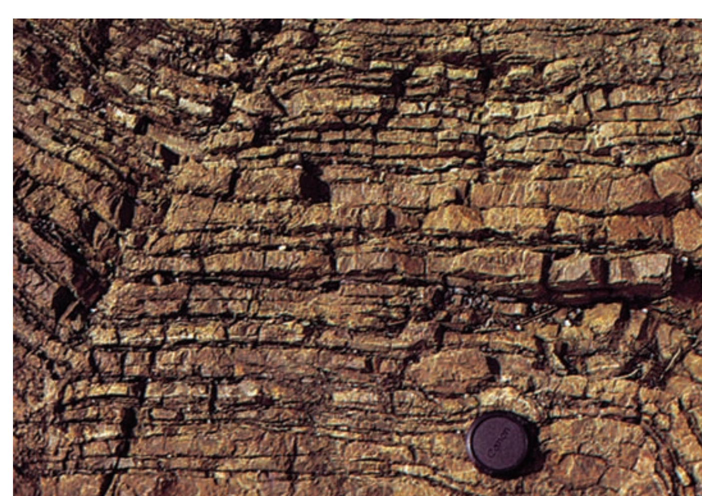
Much of the thinly interbedded dolostone and limestone that we see in the rock record is probably a result of the early replacement of reactive lime mud in shallow tidal flat environments.

Dolomite also forms when pressure and temperature increase as a result of basin subsidence and deep burial of the carbonate sediment. Geochemists have determined that higher temperatures and pressures increase the stability of dolomite over calcite or aragonite, so carbonate rocks that have been buried often change to dolostones. This process is enhanced by hot, salty pore fluids that migrate through the carbonate material. These deep burial dolostones are also a replacement for the original carbonate material, and may contain large, clear dolomite cement crystals. Deep burial dolostones tend to be thick and widespread, and they often have increased porosity from the conversion of calcite or aragonite to dolomite. Deep burial dolomite forms slowly in geologic terms, and this mechanism does not explain the shallow interbedded limestones and dolostones that are common in the rock record.

Chert

A hard, compact, fine-grained sedimentary rock formed almost entirely of silica, **chert** occurs in two principal forms—as irregular, lumpy nodules within other rocks and as layered deposits like other sedimentary rocks (figure 6.21). The nodules, often found in limestone, probably formed from inorganic

A



B

FIGURE 6.21

(*A*) Chert nodules in limestone near Bluefield, West Virginia. (*B*) Bedded chert from the coast ranges, California. Camera lens cap (5.5 centimeters) for scale. *Photo A © Parvinder Sethi; Photo B by David McGeary*

IN GREATER DEPTH 6.1

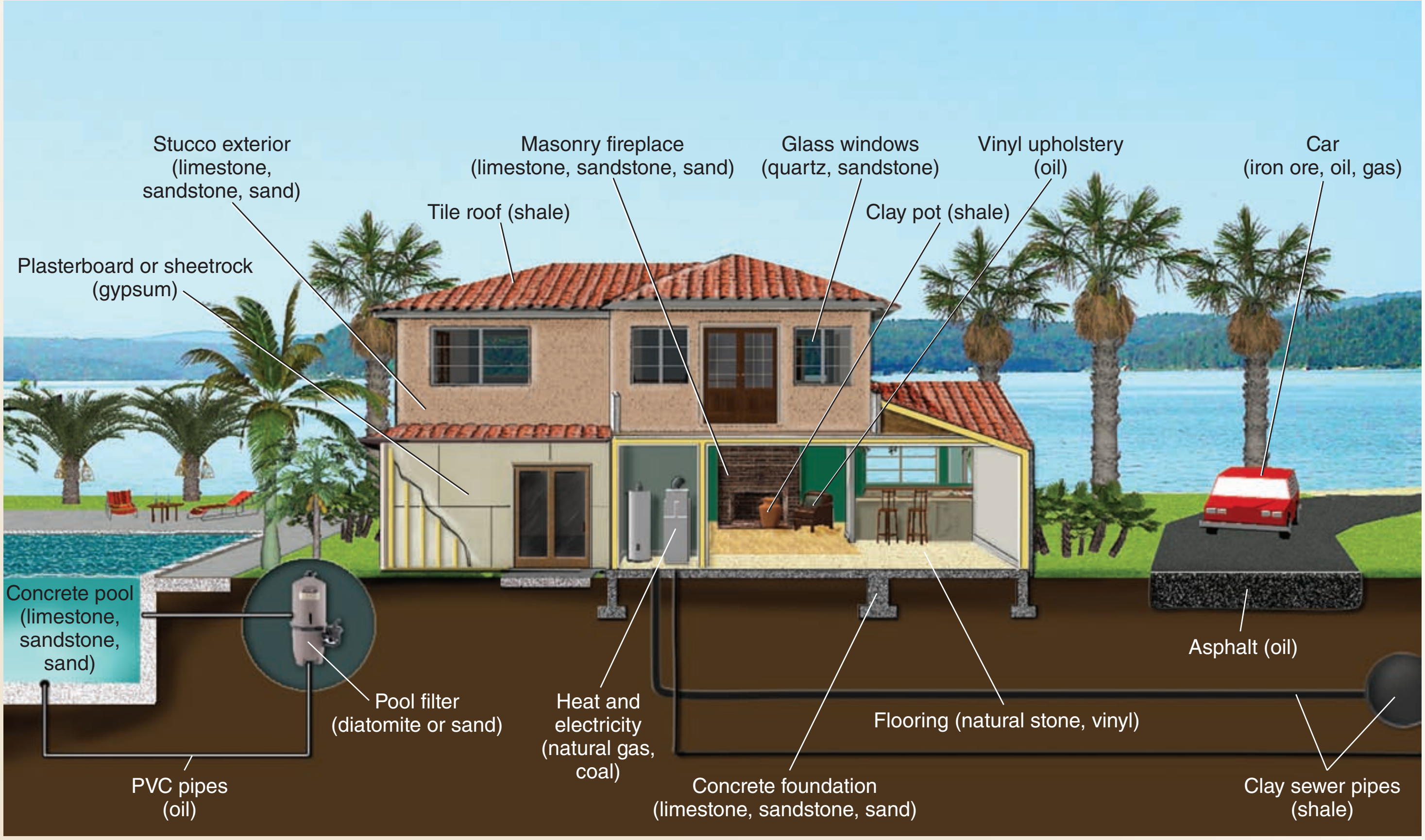
Valuable Sedimentary Rocks

Many sedimentary rocks have uses that make them valuable. *Limestone* is widely used as building stone and is also the main rock type quarried for crushed rock for road construction. Pulverized limestone is the main ingredient of cement for mortar and concrete and is also used to neutralize acid soils in the humid regions of the United States. *Coal* is a major fuel, used widely for generating electrical power and for heating. Plaster and plasterboard for home construction are manufactured from *gypsum,* which is also used to stabilize the shrink-swell characteristics of clay-rich soils in some areas. Huge quantities of *rock salt* are consumed by industry, primarily for the manufacture of hydrochloric acid. More familiar uses of rock salt are for table salt and melting ice on roads.

Some *chalk* is used in the manufacture of blackboard chalk, although most classroom chalk is now made from pulverized limestone. The filtering agent for beer brewing and for swimming pools is likely to be made of *diatomite,* an accumulation of the siliceous remains of microscopic diatoms.

Clay from *shale* and other deposits supplies the basic material for ceramics of all sorts, from hand-thrown pottery and fine porcelain to sewer pipe. *Sulfur* is used for matches, fungicides, and sulfuric acid; and *phosphates* and *nitrates* for fertilizers are extracted from natural occurrences of special sedimentary rocks (although other sources also are used). Potassium for soap manufacture comes largely from *evaporites,* as does boron for heat-resistant cookware and fiberglass and sodium for baking soda, washing soda, and soap. *Quartz sandstone* is used in glass manufacturing and for building stone.

Many *metallic ores,* such as the most common iron ores, have a sedimentary origin. The pore space of sedimentary rocks acts as a reservoir for groundwater (chapter 11), crude oil, and natural gas. In chapter 21, we take a closer look at these resources and other useful Earth materials.



BOX 6.1 ■ FIGURE 1

Common uses of materials that are sedimentary in origin.

FIGURE 6.22

Salt deposited on the floor of a dried-up desert lake, Death Valley, California. *Photo © Michael Collier*

FIGURE 6.23

Coal bed in the Black Warrior Coal Basin, Alabama. Note the fossil tree stump preserved in place at the top of the coal. *Photo by Bret Bennington*

precipitation as underground water replaced part of the original rock with silica. The layered deposits typically form from the accumulation of delicate, glass-like shells of microscopic marine organisms on the sea floor.

Microscopic fossils composed of silica are abundant in some cherts. But because chert is susceptible to recrystallization, the original fossils are easily destroyed, and the origin of many cherts remains unknown.

Evaporites

Rocks formed from crystals that precipitate during evaporation of water are called **evaporites**. They form from the evaporation of seawater or a saline lake (figure 6.22), such as Great Salt Lake in Utah. *Rock gypsum,* formed from the mineral gypsum ($CaSO_4 \cdot 2H_2O$), is a common evaporite. *Rock salt,* composed of the mineral halite (NaCl), may also form if evaporation continues. Other less common evaporites include the borates, potassium salts, and magnesium salts. All evaporites have a crystalline texture. Extensive deposits of rock salt and rock gypsum have formed in the past where shallow, continental seas existed in hot, arid climates. Similarly, modern evaporite deposits are forming in the Persian Gulf and in the Red Sea.

ORGANIC SEDIMENTARY ROCKS

Coal

Coal is a sedimentary rock that forms from the compaction of plant material that has not completely decayed (figure 6.23). Rapid plant growth and deposition in water with a low oxygen content are needed, so shallow swamps or bogs in a temperate or tropical climate are likely environments of deposition. The plant fossils in coal beds include leaves, stems, tree trunks, and stumps with roots often extending into the underlying shales, so apparently most coal formed right at the place where the plants grew. Coal usually develops from *peat,* a brown, lightweight, unconsolidated or semiconsolidated deposit of plant remains that accumulate in wet bogs. Peat is transformed into coal largely by compaction after it has been buried by sediments.

Partial decay of the abundant plant material uses up any oxygen in the swamp water, so the decay stops and the remaining organic matter is preserved. Burial by sediment compresses the plant material, gradually driving out any water or other volatile compounds. The coal changes from brown to black as the amount of carbon in it increases. Several varieties of coal are recognized on the basis of the type of original plant material and the degree of compaction (see chapter 21).

THE ORIGIN OF OIL AND GAS

Oil and natural gas seem to originate from organic matter in marine sediment. Microscopic organisms, such as diatoms and other single-celled algae, settle to the sea floor and accumulate in marine mud. The most likely environments for this are restricted basins with poor water circulation, particularly on continental shelves. The organic matter may partially decompose, using up the dissolved oxygen in the sediment. As soon as the oxygen is gone, decay stops and the remaining organic matter is preserved.

Continued sedimentation buries the organic matter and subjects it to higher temperatures and pressures, which convert the organic matter to oil and gas. As muddy sediments compact, the gas and small droplets of oil may be squeezed out of the mud and may move into more porous and permeable sandy layers nearby. Over long periods of time, large accumulations of gas and oil can collect in the sandy layers. Both oil and gas are less dense than water, so they generally tend to rise upward through water-saturated rock and sediment. Natural gas represents the end point in petroleum maturation.

Details of the origin of coal, oil, and gas are discussed in chapter 21.

SEDIMENTARY STRUCTURES

Sedimentary structures are features found within sedimentary rock. They usually form during or shortly after deposition of the sediment but before lithification. Structures found in sedimentary rocks are important because they provide clues that help geologists determine the means by which sediment was transported and also its eventual resting place, or environment of deposition. Sedimentary structures may also reveal the orientation, or upward direction, of the deposit, which helps geologists unravel the geometry of rocks that have been folded and faulted in tectonically active regions.

One of the most prominent structures, seen in most large bodies of sedimentary rock, is **bedding**, a series of visible layers within rock (figure 6.24). Most bedding is horizontal because the sediments from which the sedimentary rocks formed were originally deposited as horizontal layers. The principle of **original horizontality** states that most water-laid sediment is deposited in horizontal or near-horizontal layers that are essentially parallel to Earth's surface. In many cases, this is also true for sediments deposited by ice or wind. If each new layer of sediment buries previous layers, a stack of horizontal layers will develop, with the oldest layer on the bottom and the layers becoming younger upward. Sedimentary rocks formed from such sediments preserve the horizontal layering in the form of beds (figure 6.24). A **bedding plane** is a nearly flat surface of deposition separating two layers of rock. A change in the grain size or composition of the particles being deposited, or a pause during deposition, can create bedding planes.

In sandstone, a thicker bed of rock will often consist of a series of thinner, inclined beds called **cross-beds** (figure 6.25). Cross-beds form because in flowing air and water, sand grains move as migrating ripples and dunes. Sand is pushed up the shallow side of the ripple to the crest, where it then avalanches down the steep side, forming a cross-bed. Cross-beds form one after the other as the ripple migrates downstream (figure 6.26). Ripples can also be preserved on the surface of a bed of sandstone, forming **ripple marks**, if they are buried by another layer of sediment (figure 6.27). Ripple marks produced by currents flowing in a single direction are asymmetrical (as discussed previously and in figures 6.27*B* and *D*). In waves, water moves back and forth, producing symmetrical wave ripples (figures 6.27*A* and *C*). Ripple marks and cross-beds can form

FIGURE 6.24

Bedding in sandstone and shale, Utah. The horizontal layers formed as one type of sediment buried another in the geologic past. The layers get younger upwards. *Photo by David McGeary*

Sedimentary Rocks: The Key To Mars' Past

Sedimentary rocks on Mars are currently being studied by planetary geologists to decipher its early history and determine if Mars was once a warmer, wetter planet. Currently, the atmosphere on Mars is too thin and its surface too cold to allow liquid water to exist (see chapter 23). But recent evidence shows that Mars was once wet enough to host lakes and seas. New observations from robotic spacecraft exploring Mars show evidence for extensive deposits of water-lain sedimentary rock. In orbit around Mars, the *Mars Global Surveyor, Mars Express,* and *Mars Reconnaissance Orbiter* spacecraft have taken thousands of high-resolution photographs, many of which reveal widespread, laterally continuous layers that appear to be sedimentary rock. For example, hundreds of layers of rock are exposed in parts of the walls of the Valles Marineris, a large chasm on Mars that resembles the Grand Canyon but is almost 4,000 kilometers (2,700 miles) long! In the Mawrth Vallis, the rock layers have been identified as thick beds of clay. Because clay minerals can form only in the presence of liquid water and because the clay beds are thick and cover such a wide geographic area, one interpretation is that large bodies of standing water may have existed on Mars. These extensive lakes would have formed very early in the planet's history and probably lasted for millions of years.

While the Mars Orbiters search from the sky, Mars Rovers and Landers have been exploring the surface of the planet. The Mars Exploration Rover named *Opportunity* landed inside a small crater with exposures of layered rock and later traversed the Martian surface to enter a larger crater with more layered rock (box figure 1). Detailed photographic and spectrographic analyses of these layered rocks have revealed sedimentary features such as cross-beds, hematite mineral concretions, and the presence of minerals such as jarosite that typically form in water. More recently, the *Phoenix Mars Lander* set down near the polar region and found frozen water in the soil under the landing site. During the *Phoenix* mission, the first wet chemical analyses done on any planet other than Earth found more evidence for the possible past occurrence of water on Mars in the form of magnesium, sodium, potassium, and chloride salts (evaporites). Subsequent analyses indicate the presence of calcium carbonate (limestone), an important discovery because carbon-containing compounds are necessary for life as we know it on Earth.

The most recent rover, the *Mars Science Laboratory* (also known as *Curiosity*), is exploring Gale Crater with a complex array of new capabilities. Gale was selected from high-resolution *Mars Reconnaissance Orbiter* images showing a long-lived and varied geologic history that included potential lake deposits. *Curiosity* has in fact found and characterized strong evidence for the long-lived existence of water at Gale, including a mudstone (lithified clay deposit) and other sedimentary materials deposited by water (box figure 2). *Curiosity* will continue to drill, sample, and analyze rocks in its trek through Mars' geologic history, and it will collaborate with *MAVEN (Mars Atmospheric* and *Volatile EvolutioN*) to investigate how the atmosphere has evolved from one dense enough to support a wetter climate to the thin atmosphere present today. More exciting discoveries are anticipated as Mars continues to be one of the most promising places to look for evidence of extraterrestrial life in our solar system.

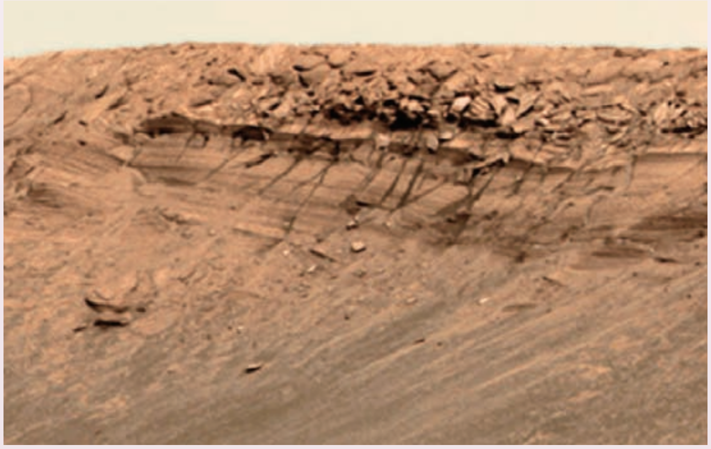
Additional Resources

Information about the Mars exploration program at NASA, including the *Mars Science Laboratory (Curiosity)* and images and updates from ongoing missions, such as the *Mars Reconnaissance Orbiter* and the *Opportunity Lander,* is available from the Jet Propulsion Laboratory/NASA Mars Program website.
http://marsprogram.jpl.nasa.gov/

Spectacular images from the *Mars Science Laboratory (Curiosity)* can be found at the MSL website.
http://mars.jpl.nasa.gov/msl/

Visit the European Space Agency's *Mars Express* website for information about this ongoing mission.
http://www.esa.int/SPECIALS/Mars_Express/

Visit the Malin Space Science Systems website for an extensive collection of archived images from recent Mars missions.
http://www.msss.com/



BOX 6.2 ■ FIGURE 1

Layers of sedimentary rock exposed inside the rim of Endurance Crater photographed by the Mars Exploration Rover *Opportunity. Photo by NASA/JPL/Cornell*

BOX 6.2 ■ FIGURE 2

Mosaic of images from the mast camera on NASA's *Curiosity* rover shows sedimentary deposits in the Glenelg area of Gale Crater. *Photo by NASA/JPL-Caltech/MSSS.*

FIGURE 6.25

Cross-bedded sandstone in Zion National Park, Utah. Note how the thin layers have formed at an angle to the more extensive bedding planes (also tilted) in the rock. This cross-bedding was formed in sand dunes deposited by the wind. *Photo by David McGeary*

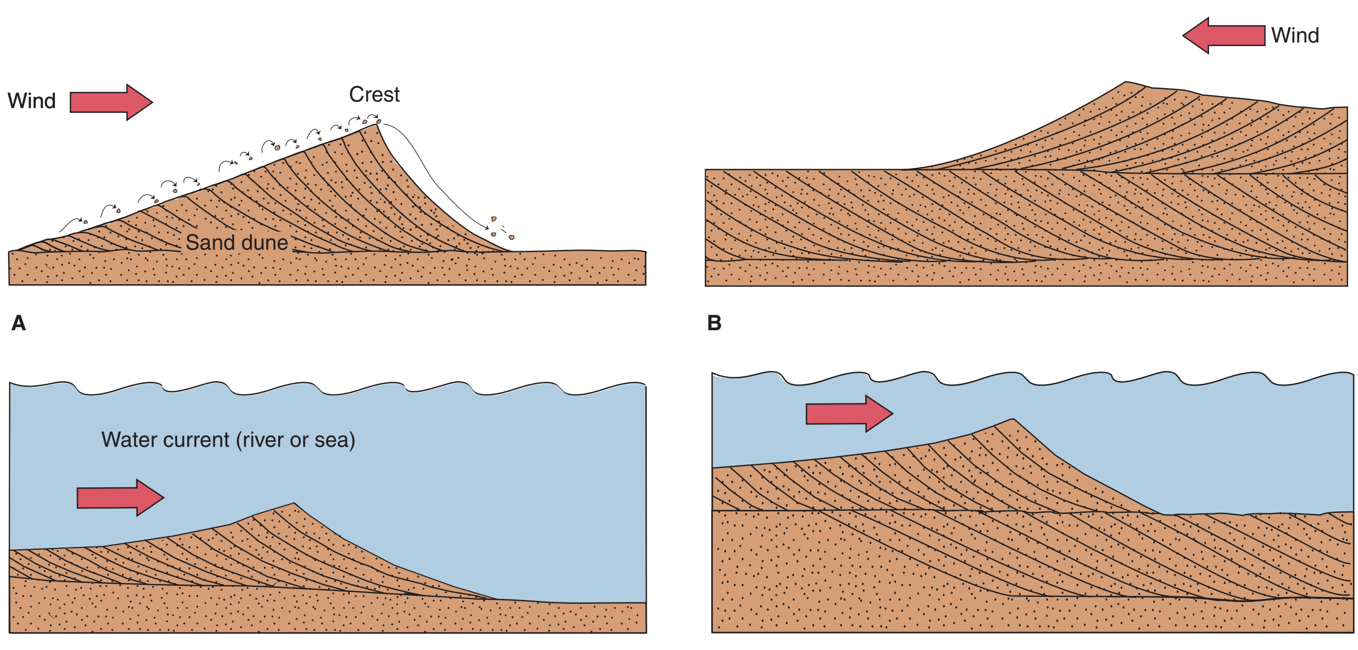


FIGURE 6.26

The development of cross-beds in wind-blown sand (*A* and *B*) and water-deposited sand (*C* and *D*). (*A*) Sand grains migrate up the shallow side of the dune and avalanche down the steep side, forming cross-beds. (*B*) Second layer of cross-beds forms as wind shifts and a dune migrates from the opposite direction. (*C*) Underwater current deposits cross-beds as ripple migrates downstream. (*D*) Continued deposition and migration of ripples produces multiple layers of cross-beds.

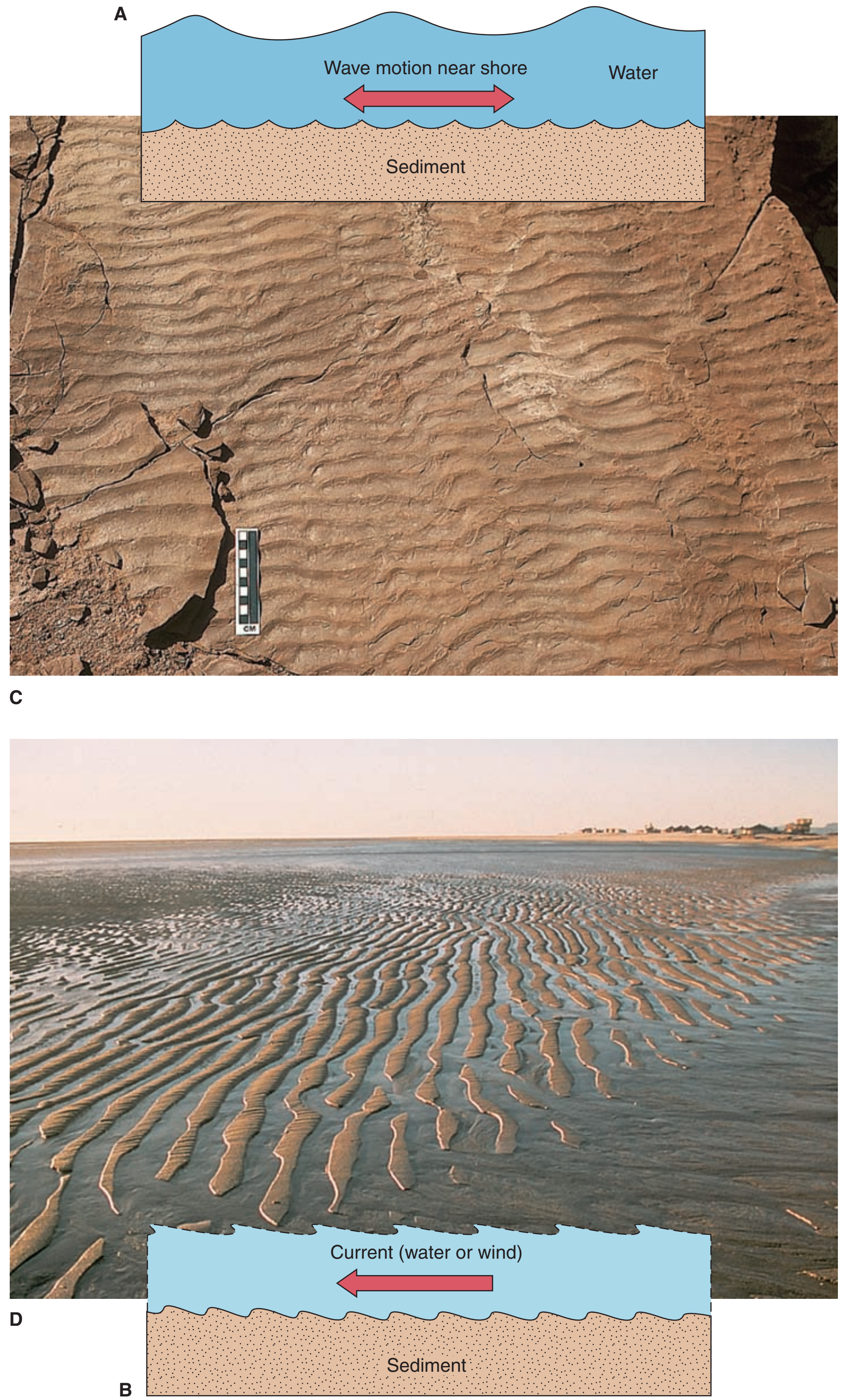


FIGURE 6.27

Development of ripple marks in loose sediment. (*A*) Symmetric ripple marks form beneath waves. (*B*) Asymmetric ripple marks, forming beneath a current, are steeper on their down-current sides. (*C*) Ripple marks on a bedding plane in sandstone, Capitol Reef National Park, Utah. Scale in centimeters. (*D*) Current ripples in wet sediment of a tidal flat, Baja California. *Photo C by David McGeary; Photo D by Frank M. Hanna* in conglomerates, sandstones, siltstones, and limestones and in environments such as deserts, river channels, river deltas, and shorelines.

A **graded bed** is a layer with a vertical change in particle size, usually from coarse grains at the bottom of the bed to progressively finer grains toward the top (figure 6.28). A single bed may have gravel at its base and grade upward through sand and silt to fine clay at the top. A graded bed may be deposited by a turbidity current. A **turbidity current** is a turbulently flowing mass of sediment-laden water that is heavier than clear water and therefore flows downslope along the bottom of the sea or a lake. Turbidity currents are underwater avalanches and are typically triggered by earthquakes or submarine landslides. Figure 6.29 shows the development of a graded bed by turbidity-current deposition.

Mud cracks are a polygonal pattern of cracks formed in very fine-grained sediment as it dries (figure 6.30). Because drying requires air, mud cracks form only in sediment exposed above water. Mud cracks may form in lake-bottom sediment as the lake dries up; in flood-deposited sediment as a river level drops; or in marine sediment exposed to the air, perhaps temporarily by a falling tide. Cracked mud can lithify to form shale, preserving the cracks. The filling of mud cracks by sand can form casts of the cracks in an overlying sandstone.

FOSSILS

Fossils are the remains of organisms preserved in sedimentary rock. Most sedimentary layers contain some type of fossil, and some limestones are composed entirely of fossils. Most fossils are preserved by the rapid burial in sediment of bones, shells, or teeth, which are the mineralized hard parts of animals most resistant to decay (figure 6.31). The original bone or shell is rarely preserved unaltered; the original mineral is often recrystallized or replaced by a different mineral such as pyrite or silica. Bone and wood may be *petrified* as organic material is replaced and pore spaces filled with mineral. Shells entombed within rock are commonly dissolved away by pore waters, leaving only impressions or *molds* of the original fossil. Leaves and undecayed organic tissue can also be preserved as thin films of carbon (figure 6.32*A*). *Trace fossils* are a type of sedimentary structure produced by the impact of an organisms's activities on the sediment. Footprints, trackways, and burrows are the most common trace fossils (figure 6.32*B*).

Many *paleontologists* study fossils to learn about the evolution of life on Earth, but fossils are also very useful for interpreting depositional environments and for reconstructing the climates of the past. Fossils can be used to distinguish freshwater from marine environments and to infer the water depth at which a particular sedimentary layer was deposited. Tropical, temperate, and arid climates can be associated with distinctive types of fossil plants. Marine *microfossils,* the tiny shells produced by ocean-dwelling plankton, can be analyzed to determine the water temperature that surrounded the shell

FIGURE 6.28

A graded bed has coarse grains at the bottom of the bed and progressively finer grains toward the top. Coin for scale. *Photo by David McGeary*

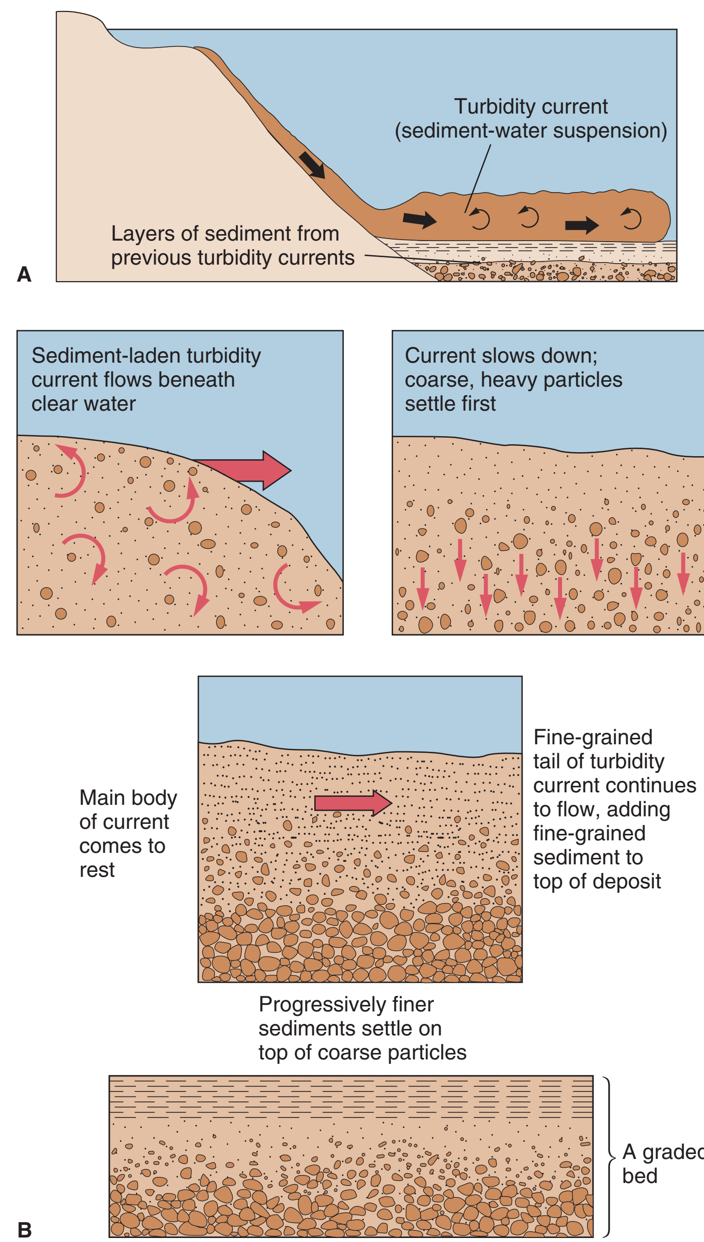
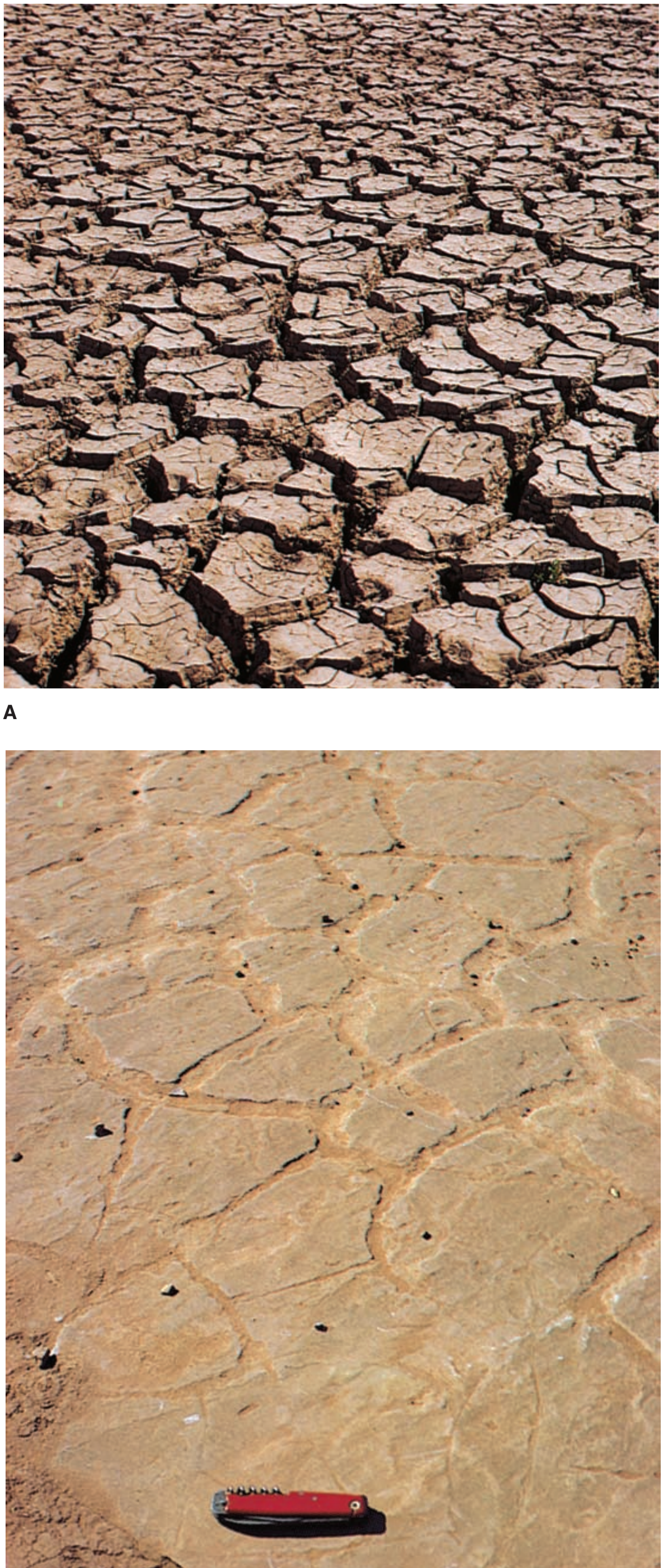


FIGURE 6.29

Formation of a graded bed by deposition from a turbidity current. (*A*) Slurry of sediment and water moves downslope along the sea floor. (*B*) As the turbidity flow slows down, larger grains are deposited first, followed by progressively finer grains, to produce a graded bed.



A

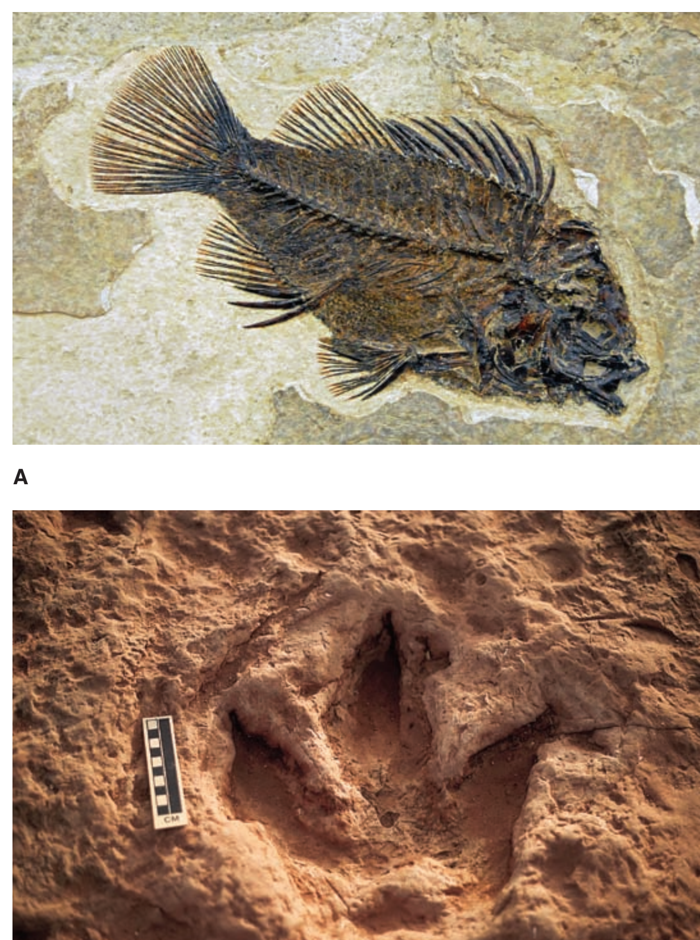
B

FIGURE 6.30

(*A*) Mud cracks in recently dried mud. (*B*) Mud cracks preserved in shale; they have been partially filled with sediment. *Photos by David McGeary*

FIGURE 6.31

Fossil clams, brachiopods, and trilobites in the Hamilton Shale of New York. Some of the fossils have their original shell material; other fossils are preserved as impressions. *Photo by Bret Bennington*



A

B

FIGURE 6.32

(*A*) Fossil fish in a rock from western Wyoming. (*B*) Dinosaur footprint in shale, Tuba City, Arizona. Scale in centimeters. *Photo A © Alan Morgan RF; Photo B by David McGeary* when it formed. Much of our detailed knowledge of Earth's climate changes over the last 150 million years has come from the study of microfossils extracted from layers of mud deposited on the deep-ocean floor.

FORMATIONS

A **formation** is a body of rock of considerable thickness that is large enough to be mappable, and with characteristics that distinguish it from adjacent rock units. Although a formation is usually composed of one or more beds of sedimentary rock, units of metamorphic and igneous rock are also called formations. It is a convenient unit for mapping, describing, or interpreting the geology of a region.

Formations are often based on rock type. A formation may be a single thick bed of rock such as sandstone. A sequence of several thin sandstone beds could also be called a formation, as could a sequence of alternating limestone and shale beds.

The main criterion for distinguishing and naming a formation is some visible characteristic that makes it a recognizable unit. This characteristic may be rock type or sedimentary structures or both. For example, a thick sequence of shale may be overlain by basalt flows and underlain by sandstone. The shale, the basalt, and the sandstone are each a different formation. Or a sequence of thin limestone beds, with a total thickness of many tens of meters, may have recognizable fossils in the lower half and distinctly different fossils in the upper half. The limestone sequence is divided into two formations on the basis of its fossil content.

Formations are given proper names: the first name is often a geographic location where the rock is well exposed, and the second is the name of a rock type, such as Navajo Sandstone, Austin Chalk, Baltimore Gneiss, Onondaga Limestone, or Chattanooga Shale. If the formation has a mixture of rock types, so that one rock name does not accurately describe it, it is called simply "formation," as in the Morrison Formation or the Martinsburg Formation.

A **contact** is the boundary surface between two different rock types or ages of rocks. In sedimentary rock formations, the contacts are usually bedding planes.

Figure 6.33 shows the three formations that make up the upper part of the canyon walls in Grand Canyon National Park in Arizona. The contacts between formations are also shown.

FIGURE 6.33

The upper three formations in the cliffs of the Grand Canyon, Arizona. The Kaibab Limestone and the Coconino Sandstone are resistant in the dry climate and form cliffs. The Toroweap Formation contains some shale and is less resistant, forming slopes. The gray lines are drawn to show the approximate contacts or boundaries between the formations. *Photo by David McGeary*

INTERPRETATION OF SEDIMENTARY ROCKS

Sedimentary rocks are important in interpreting the geologic history of an area. Geologists examine sedimentary formations to look for clues such as fossils; sedimentary structures; grain shape, size, and composition; and the overall shape and extent of the formation. These clues are useful in determining the source area of the sediment, environment of deposition, and the possible plate-tectonic setting at the time of deposition.

Source Area

The **source area** of a sediment is the locality that eroded and provided the sediment. The most important things to determine about a source area are the types of rocks that were exposed in it and its location and distance from the site of eventual deposition.

The *rock type* exposed in the source area determines the character of the resulting sediment. The composition of a sediment can indicate the source area rock type, even if the source area has been completely eroded away. A conglomerate may contain cobbles of basalt, granite, and chert; these rock types were obviously in its source area. An arkose containing coarse feldspar, quartz, and biotite may have come from a granitic source area. Furthermore, the presence of feldspar indicates the source area was not subjected to extensive chemical weathering and that erosion probably took place in an arid environment with high relief. A quartz sandstone containing well-rounded quartz grains, on the other hand, probably represents the erosion and deposition of quartz grains from preexisting sandstone. Quartz is a hard, tough mineral very resistant to rounding by abrasion, so if quartz grains are well-rounded, they have undergone many cycles of erosion, transportation, and deposition, probably over tens of millions of years.

Sedimentary rocks are also studied to determine the *direction* and *distance* to the source area. Figure 6.34 shows how several characteristics of sediment may vary with distance from a source area. Many sediment deposits get thinner away from the source, and the sediment grains themselves usually become finer and more rounded.

Sedimentary structures often give clues about the directions of ancient currents (*paleocurrents*) that deposited sediments. Refer back to figure 6.25 and notice how cross-beds slope downward in the direction of current flow. Ancient current direction can also be determined from asymmetric ripple marks (figures 6.27*C* and *D*).

Environment of Deposition

Figure 6.35 shows the common environments in which sediments are deposited. Geologists study modern environments in great detail so that they can interpret ancient rocks. Clues to the ancient environment of deposition come from a rock's composition, the size and sorting and rounding of the grains, the sedimentary structures and fossils present, and the vertical sequence of the sedimentary layers.

Continental environments include alluvial fans, river channels, flood plains, lakes, and dunes. Sediments deposited on land are subject to erosion, so they often are destroyed. The great bulk of sedimentary rocks comes from the more easily preserved shallow marine environments, such as deltas, beaches, lagoons, shelves, and reefs. The characteristics of major environments are covered in detail in later chapters (10, 12–14, 18). In this section, we describe the main sediment types and sedimentary structures found in each environment.

Glacial Environments

Glacial ice often deposits narrow ridges and layers of sediment in valleys and widespread sheets of sediment on plains. Glacial sediment (*till*) is an unsorted mix of unweathered boulders, cobbles, pebbles, sand, silt, and clay. The boulders and cobbles may be scratched from grinding over one another under the great weight of the ice.

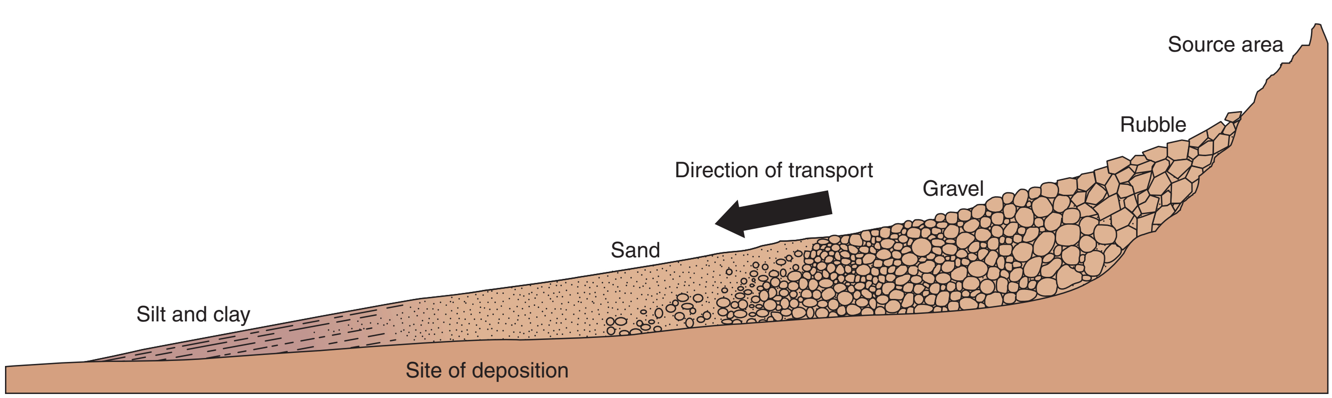


FIGURE 6.34

Sediment deposits often become thinner away from the source area, and sediment grains usually become finer and more rounded. The rocks that form from these sediments would change with distance from the source area from breccia to conglomerate to sandstone to shale. See appendix F for rock symbols.

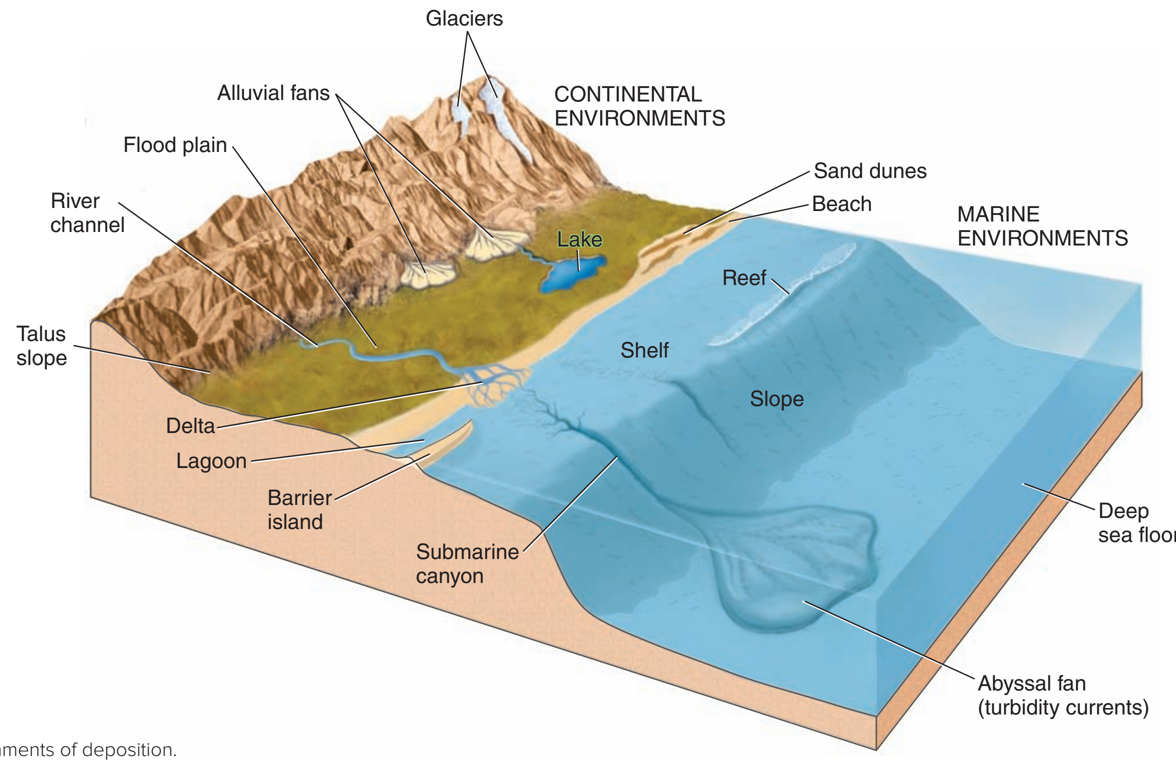
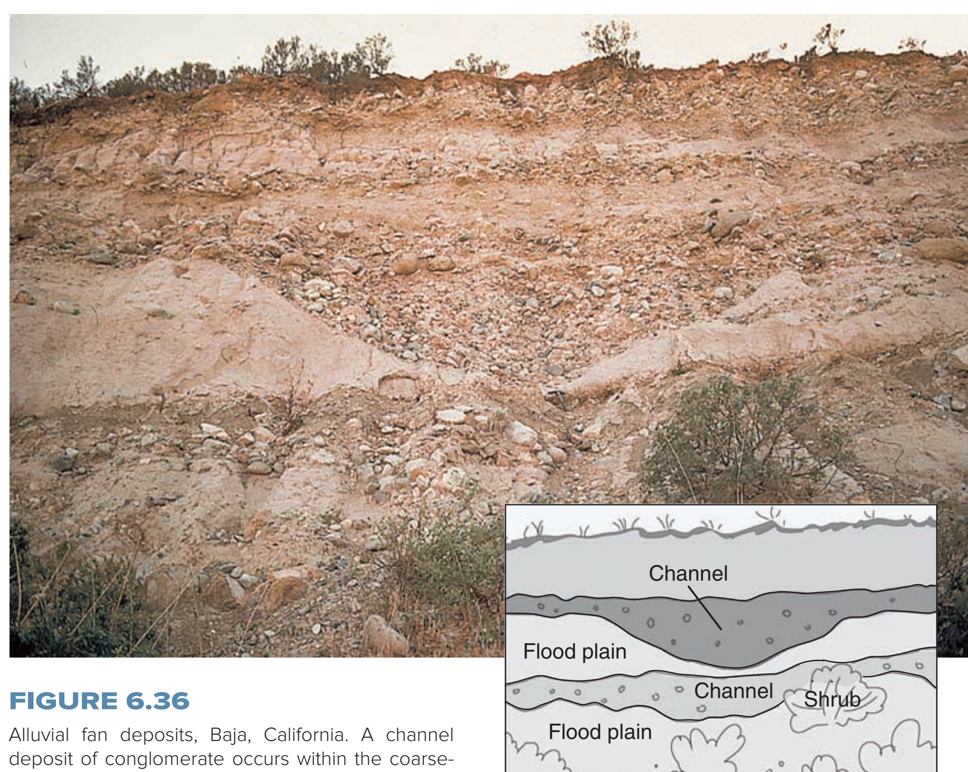


FIGURE 6.35

The common sedimentary environments of deposition.

Alluvial Fan

As streams emerge from mountains onto flatter plains, they deposit broad, fan-shaped piles of sediment. The sediment often consists of coarse, arkosic sandstones and conglomerates, marked by coarse cross-bedding and lens-like channel deposits (figure 6.36).



Geologist's View

FIGURE 6.36

Alluvial fan deposits, Baja, California. A channel deposit of conglomerate occurs within the coarse-grained sequence. *Photo by David McGeary*

River Channel and Flood Plain

Rivers deposit elongate lenses of conglomerate or sandstone in their channels (figure 6.37). The sandstones may be arkoses or may consist of sand-sized fragments of fine-grained rocks. River channel deposits typically contain cross-beds and current ripple marks. Broad, flat flood plains are covered by periodic floodwaters, which deposit thin-bedded shales characterized by mud cracks and fossil footprints of animals. Hematite may color flood-plain deposits red.

Lake

Thin-bedded shale, perhaps containing fish fossils, is deposited on lake bottoms. If the lake periodically dries up, the shales will be mud-cracked and perhaps interbedded with evaporites such as gypsum or rock salt.

Delta

A delta is a body of sediment deposited when a river flows into standing water, such as the sea or a lake. Most deltas contain a great variety of subenvironments but are generally made up of thick sequences of siltstone and shale, marked by low-angle cross-bedding and cut by coarser channel deposits. Delta sequences may contain beds of peat or coal, as well as marine fossils such as clam shells.

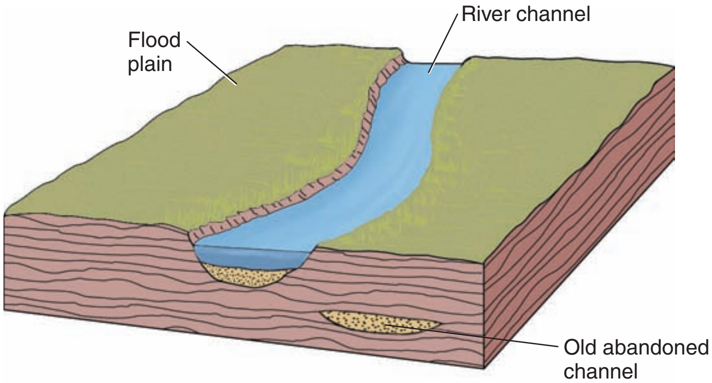


FIGURE 6.37

A river deposits an elongate lens of sand and gravel in its channel. Fine-grained silt and clay are deposited beside the channel on the river's flood plain.

Beach, Barrier Island, Dune

A barrier island is an elongate bar of sand built by wave action. Well-sorted quartz sandstone with well-rounded grains is deposited on beaches, barrier islands, and dunes. Beaches and barrier islands are characterized by cross-bedding (often low-angle) and marine fossils. Dunes have both high-angle and low-angle cross-bedding and occasionally contain fossil footprints of land animals such as lizards. All three environments can also contain carbonate sand in tropical regions, thus yielding cross-bedded clastic limestones.

Lagoon

A semienclosed, quiet body of water between a barrier island and the mainland is a lagoon. Fine-grained dark shale, cut by tidal channels of coarse sand and containing fossil oysters and other marine organisms, is formed in lagoons. Limestones may also form in lagoons adjacent to reefs (see figure 6.15).

Shallow Marine Shelves

On the broad, shallow shelves adjacent to most shorelines, sediment grain size decreases offshore. Widespread deposits of sandstone, siltstone, and shale can be deposited on such shelves. The sandstone and siltstone contain symmetrical ripple marks, low-angle cross-beds, and marine fossils such as clams and snails. If fine-grained *tidal flats* near shore are alternately covered and exposed by the rise and fall of tides, mud-cracked marine shale will result.

Reefs

Massive limestone forms in reef cores, with steep beds of limestone breccia forming seaward of the reef, and horizontal beds of sand-sized and finer-grained limestones forming landward (see figure 6.15). All these limestones are full of fossil fragments of corals, coralline and calcareous algae, and numerous other marine organisms.

Deep Marine Environments

On the deep-sea floor are deposited shale and graywacke sandstones. The graywackes are deposited by turbidity currents (figure 6.29) and typically contain graded bedding and current ripple marks.

Transgression and Regression

Sea level is not stable. Sea level has risen and fallen many times in the geologic past, flooding and exposing much of the land of the continents as it did so.

On a very broad, shallow marine shelf, several types of sediments may be deposited. On the beach and near shore, waves will deposit sand, which is usually derived from land. Farther from shore, in deeper, quieter water, land-derived silt and clay will be deposited. If the shelf is broad enough and covered with warm water, corals and algae may form carbonate sediments still farther seaward, beyond the reach of land-derived sediment. These sediments can lithify to form a seaward sequence of sandstone, shale, and limestone (figure 6.38*A*).

If sea level rises or the land sinks (subsides), large areas of land will be flooded, and these three environments of rock deposition will migrate across the land (figure 6.38*B*). This is a *transgression* of the sea as it moves across the land, and it can result in a bed of sandstone overlain by shale, which in turn is overlain by limestone (transgressive sequence). Note that different parts of a single rock bed are deposited at different times—the seaward edge of the sandstone bed, for example, is older than the landward edge.

In a *regression* the sea moves off the land and the three rock types are arranged in a new vertical sequence—limestone is overlain by shale and shale by sandstone (figure 6.38*C*). A drop in sea level alone will not preserve this regressive sequence of rocks. The land must usually subside rapidly to preserve these rocks so that they are not destroyed by continental erosion.

The angles shown in the figure are exaggerated—the rocks often appear perfectly horizontal. Geologists use these two contrasting vertical sequences of rock to identify ancient transgressions and regressions.

Tectonic Setting of Sedimentary Rocks

The dynamic forces that move plates on Earth are also responsible for the distribution of many sedimentary rocks. As such, the distribution of sedimentary rocks often provides information that helps geologists reconstruct past plate-tectonic settings.

In tectonically active areas, particularly along *convergent plate boundaries,* the thickening of the crust that forms a mountain belt also causes the adjacent crust to subside, forming basins (figure 6.39). Rapid erosion of the rising mountains produces enormous quantities of sediment that are transported by streams and turbidity currents to the adjacent basins. Continued subsidence of the basins results in the formation of great thicknesses of sedimentary rock that record the history of uplift and erosion in the mountain belt. For example, uplift of the ancestral Sierra Nevada and Klamath mountain ranges in California is recorded by the thick accumulation of turbidite deposits preserved in basins to the west of the mountains. There, graywacke sandstone deposited by turbidity currents

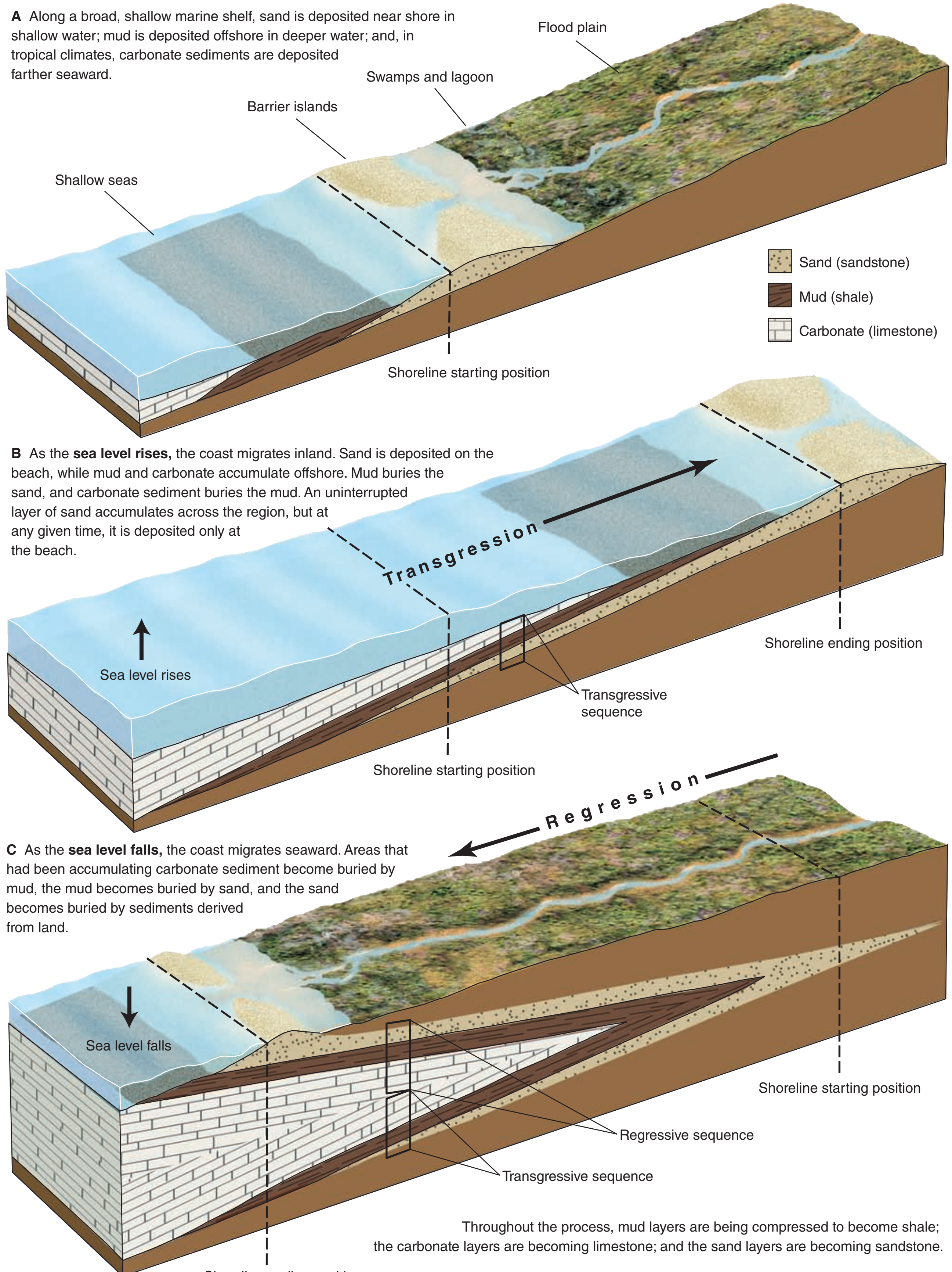


FIGURE 6.38

Transgressions and regressions of the sea can form distinctive sequences of sedimentary rocks.

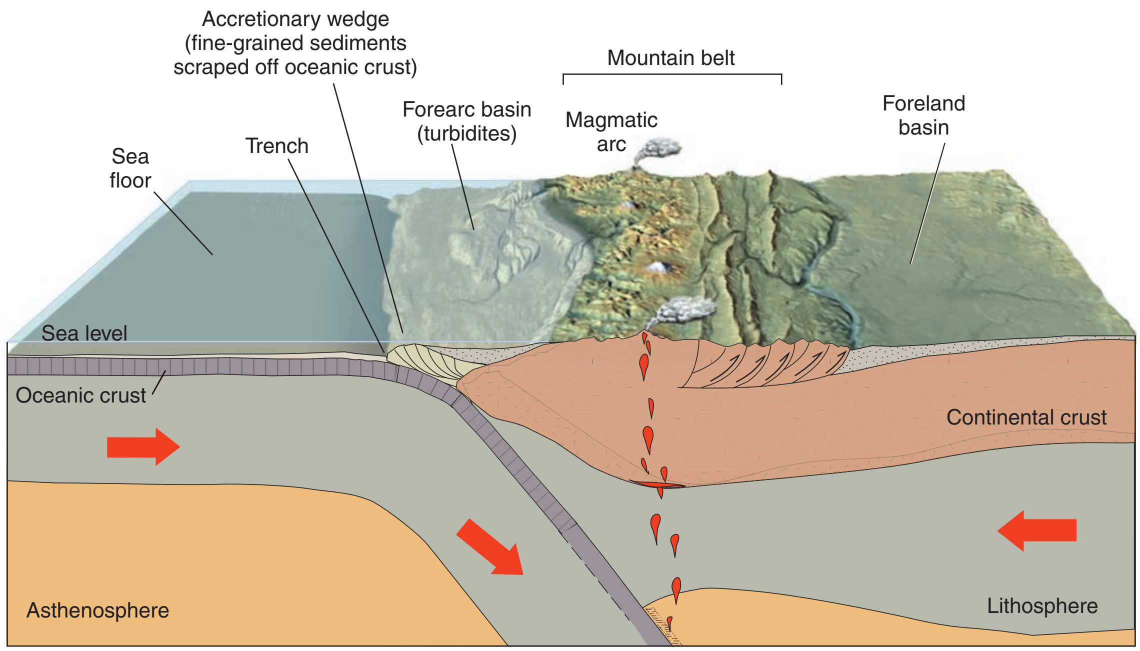


FIGURE 6.39

Sedimentary basins associated with convergent plate boundary include a forearc basin on the oceanward side that contains mainly clastic sediments deposited by streams and turbidity currents from an eroding magmatic arc. Toward the craton (continent), a foreland basin also collects clastic sediment derived from the uplifted mountain belt and craton.

contains mainly volcanic clasts in the lower part of the sedimentary sequence and abundant feldspar clasts in the upper part of the sequence. This indicates that a cover of volcanic rocks was first eroded from the ancestral mountains, and then, as uplift and erosion continued, the underlying plutonic rocks were exposed and eroded. Other eroded mountains, such as the Appalachians, have left similar records of uplift and erosion in the sedimentary record.

It is not uncommon for rugged mountain ranges, such as the Canadian Rockies, European Alps, and Himalayas, that stand several thousand meters above sea level to contain sedimentary rocks of marine origin that were originally deposited below sea level. The presence of marine sedimentary rocks such as limestone, chert, and shale containing marine fossils at high elevations attests to the tremendous uplift associated with mountain building at convergent plate boundaries (see chapter 20).

Transform plate boundaries are also characterized by rapid rates of erosion and deposition of sediments as fault-bounded basins open and subside rapidly with continued plate motion. Because of the rapid rate of deposition and burial of organic material, fault-bounded basins are good places to explore for petroleum. Many of the petroleum occurrences in California are related to basins that formed as the San Andreas transform fault developed.

A *divergent plate boundary* may result in the splitting apart of a continent and formation of a new ocean basin. In the initial stages of continental divergence, a rift valley forms and fills with thick wedges of gravel and coarse sand along its fault-bounded margins; lake bed deposits and associated evaporite rocks may form in the bottom of the rift valley (figure 6.40). In the early stages, continental rifts will have extensive volcanics that contribute to the sediments in the rift. The Red Sea and adjacent East African Rift Zone have good examples of the features and sedimentary rocks formed during the initial stages of continental rifting.

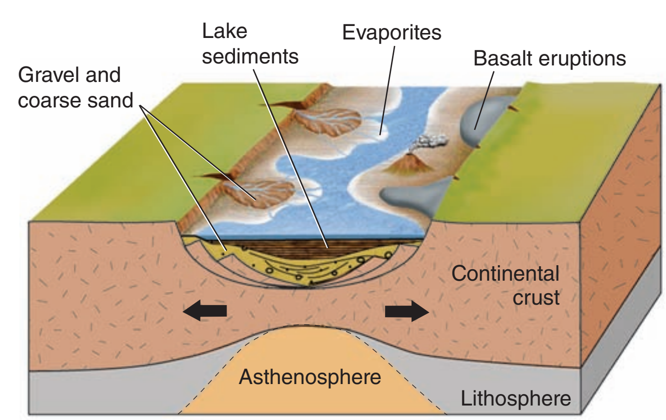


FIGURE 6.40

Divergent plate boundary showing thick wedges of gravel and coarse sand along fault-bounded margins of developing rift valley. Lake bed deposits and evaporite rocks are located on the floor of the rift valley. Refer to figures 19.20 and 19.22 for more detail of faulted margin and sediments deposited along a rifted continental margin.

Summary

Sediment forms by the weathering and erosion of preexisting rocks and by chemical precipitation, sometimes by organisms.

Gravel, sand, silt, and *clay* are sediment particles defined by grain size.

The composition of sediment is governed by the rates of chemical weathering, mechanical weathering, and erosion. During transportation, grains can become rounded and sorted.

Sedimentary rocks form by *lithification* of sediment, by *crystallization* from solution, or by consolidation of remains of organisms. Sedimentary rocks may be *detrital, chemical,* or *organic.*

Detrital sedimentary rocks form mostly by *compaction* and *cementation* of grains. *Matrix* can partially fill the *pore space* of clastic rocks.

Conglomerate forms from coarse, rounded sediment grains that often have been transported only a short distance by a river or waves. *Sandstone* forms from sand deposited by rivers, wind, waves, or turbidity currents. *Shale* forms from river, lake, or ocean mud.

Limestone consists of calcite, formed either as a chemical precipitate in a reef or, more commonly, by the cementation of shell and coral fragments or of oöids. *Dolomite* usually forms from the alteration of limestone by magnesium-rich solutions.

Chert consists of silica and usually forms from the accumulation of microscopic marine organisms. *Recrystallization* often destroys the original texture of chert (and some limestones).

Evaporites, such as rock salt and gypsum, form as water evaporates. *Coal,* a major fuel, is consolidated plant material.

Sedimentary rocks are usually found in *beds* separated by *bedding planes* because the original sediments are deposited in horizontal layers.

Cross-beds and *ripple marks* develop as moving sediment forms ripples and dunes during transport by wind, underwater currents, and waves.

A *graded bed* forms as coarse particles fall from suspension before fine particles due to decreasing water flow velocity in a *turbidity current.*

Mud cracks form in drying mud.

Fossils are the traces of an organism's hard parts or tracks preserved in rock.

A *formation* is a convenient rock unit for mapping and describing rock. Formations are lithologically distinguishable from adjacent rocks; their boundaries are *contacts.*

Geologists try to determine the *source area* of a sedimentary rock by studying its grain size, composition, and sedimentary structures. The source area's rock type and location are important to determine.

The *environment of deposition* of a sedimentary rock is determined by studying bed sequence, grain composition and rounding, and sedimentary structures. Typical environments include alluvial fans, river channels, flood plains, lakes, dunes, deltas, beaches, shallow marine shelves, reefs, and the deep-sea floor.

Plate tectonics plays an important role in the distribution of sedimentary rocks; the occurrence of certain types of sedimentary rocks is used by geologists to construct past plate-tectonic settings.

Terms to Remember

alluvial fan 133
bedding 143
bedding plane 143
cement 131
cementation 131
chemical sedimentary rocks 132
chert 140
clastic texture 132
clay 129
coal 142
compaction 131
conglomerate 132
contact 149
cross-beds 143
crystalline texture 132
crystallization 132
deposition 130
detrital sedimentary rocks 132
dolomite 139
environment of deposition 130
evaporite 142
formation 149
fossil 147
graded bed 147
gravel 129
limestone 136
lithification 131
matrix 133
mud crack 147
organic sedimentary rock 132
original horizontality 143
pore space 131
recrystallization 137
ripple marks 143
rounding 129
sand 129
sandstone 133
sediment 128
sedimentary breccia 132
sedimentary rocks 132
sedimentary structures 143
shale 133
silt 129
sorting 129
source area 150
transportation 129
turbidity current 147

Testing Your Knowledge

Use the following questions to prepare for exams based on this chapter.

1. Quartz is a common mineral in sandstone. Under certain circumstances, feldspar is common in sandstone, even though it normally weathers rapidly to clay. What conditions of climate, weathering rate, and erosion rate could lead to a feldspar-rich sandstone? Explain your answer.
2. Describe with sketches how wet mud compacts before it becomes shale.
3. What do mud cracks tell us about the environment of deposition of a sedimentary rock?
4. How does a graded bed form?
5. List the detrital sediment particles in order of decreasing grain size.
6. How does a sedimentary breccia differ in appearance and origin from a conglomerate?
7. Describe three different origins for limestone.
8. How does dolomite usually form?
9. What is the origin of coal?

10. Sketch the cementation of sand to form sandstone.
11. How do evaporites form? Name two evaporites.
12. Name the three most common sedimentary rocks.
13. What is a formation?
14. Explain two ways that cross-bedding can form.
15. Particles of sediment from 1/16 to 2 millimeters in diameter are of what size?

    a. gravel b. sand
    c. silt d. clay
16. Rounding is

    a. the rounding of a grain to a spherical shape.
    b. the grinding away of sharp edges and corners of rock fragments during transportation.
    c. a type of mineral.
    d. none of the preceding.
17. Compaction and cementation are two common processes of

    a. erosion. b. transportation.
    c. deposition. d. lithification.
18. Which is *not* a chemical or organic sedimentary rock?

    a. rock salt b. sandstone
    c. limestone d. gypsum
19. The major difference between breccia and conglomerate is

    a. size of grains.
    b. rounding of the grains.
    c. composition of grains.
    d. all of the preceding.
20. Which is *not* a type of sandstone?

    a. quartz sandstone b. arkose
    c. graywacke d. travertine
21. Shale differs from mudstone in that

    a. shale has larger grains.
    b. shale is visibly layered and fissile; mudstone is massive and blocky.
    c. shale has smaller grains.
    d. there is no difference between shale and mudstone.
22. The chemical element found in dolomite *not* found in limestone is

    a. Ca. b. Mg.
    c. C. d. O.
    e. Al.
23. In a graded bed, the particle size

    a. decreases upward.
    b. decreases downward.
    c. increases in the direction of the current.
    d. stays the same.
24. A body or rock of considerable thickness with characteristics that distinguish it from adjacent rock units is called a/an

    a. formation. b. contact.
    c. bedding plane. d. outcrop.
25. If sea level drops or the land rises, what is likely to occur?

    a. a flood b. a regression
    c. a transgression d. no geologic change will take place
26. Thick accumulations of graywacke and volcanic sediments can indicate an ancient

    a. divergent plate boundary.
    b. convergent boundary.
    c. transform boundary.
27. A sedimentary rock made of fragments of preexisting rocks is

    a. organic. b. chemical.
    c. detrital.
28. Clues to the nature of the source area of sediment can be found in

    a. the composition of the sediment.
    b. sedimentary structures.
    c. rounding of sediment.
    d. all of the preceding.

Expanding Your Knowledge

1. How might graded bedding be used to determine the tops and bottoms of sedimentary rock layers in an area where sedimentary rock is no longer horizontal? What other sedimentary structures can be used to determine the tops and bottoms of tilted beds?
2. Which would weather faster in a humid climate, a quartz sandstone or an arkose? Explain your answer.
3. A cross-bedded quartz sandstone may have been deposited as a beach sand or as a dune sand. What features could you look for within the rock to tell whether it had been deposited on a beach? On a dune?
4. Why is burial usually necessary to turn a sediment into a sedimentary rock?
5. Why are most beds of sedimentary rock formed horizontally?
6. Discuss the role of sedimentary rocks in the rock cycle, diagramming the rock cycle as part of your answer. What do sedimentary rocks form from? What can they turn into?

Exploring Web Resources

http://pages.uoregon.edu/~rdorsey/SedResources.html

Web Resources for Sedimentary Geology site contains a comprehensive listing of resources available on the World Wide Web.

www.lib.utexas.edu/geo/folkready/folkprefrev.html

Online version of *Petrology of Sedimentary Rocks* by Professor Robert Folk at the University of Texas at Austin.

http://walrus.wr.usgs.gov/seds/

Visit the *U.S. Geological Survey Bedform and Sedimentology* site for computer and photographic images and movies of sedimentary structures.