5 Sedimentary Rocks

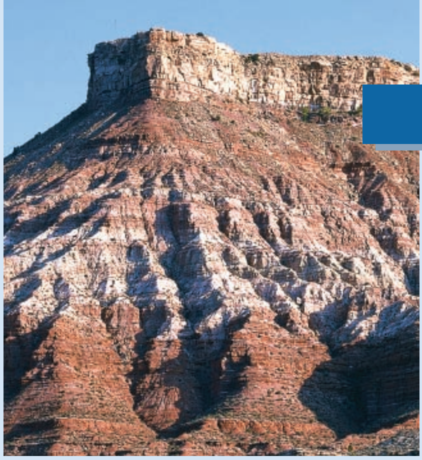
The geologic processes operating on Earth's surface produce only subtle changes in the landscape during a human lifetime, but over a period of tens of thousands or millions of years, the effect of these processes is considerable. Given enough time, the erosive power of the hydrologic system can reduce an entire mountain range to a featureless lowland. In the process, the eroded debris is transported by rivers and deposited as new layers of sedimentary rock.

A series of sedimentary rock layers may be thousands of meters thick. When exposed at the surface, each rock layer provides information about past events in Earth's history. Such is the case in the Moenkopi Formation of southern Utah shown in the panorama above. The various shades of red and white occur in the thin beds of siltstone and mudstone deposited on an ancient tidal flat about 220 million years ago. Thin layers of siltstone and shale each contining ripple marks, mudcracks, and rain imprints combine to tell the history recorded in the rock now exposed in this colorful cliff.

The record of Earth's history preserved in sedimentary rocks is truly remarkable. Each bedding plane is a remnant of what was once the surface of Earth. Each rock layer is the product of a previous period of erosion and deposition. In addition, details of texture, composition, and fossils are important records of global change, showing how Earth

evolved in the past and how it may change in the future. To interpret the sedimentary record correctly, we must first understand something about modern sedimentary systems, the sources of sediment, transportation pathways, and places where sediment is accumulating today, such as deltas, beaches, and rivers. The study of how modern sediment originates and is deposited provides insight into how ancient sedimentary rocks formed. Fossils preserved in sedimentary rocks not only reveal the environment of deposition but also the pace and course of evolution through Earth's long life.

Apart from their scientific significance, the sedimentary rocks have been a controlling factor in the development of industry, society, and culture. Humans have used materials from sedimentary rocks since the Neolithic Age; flint and chert played an important role in the development of tools, arrowheads, and axes. The great cathedrals of Europe are made from sedimentary rock, and the statues made by the artists of ancient Greece and Rome and during the Renaissance would have been impossible without limestone. Fully 85% to 90% of mineral products used by our society come from sedimentary rocks. Virtually our entire store of petroleum, natural gas, coal, and fertilizer come from sedimentary rocks. Sand, gravel, and limestone are the raw materials for cement. Sedimentary rocks are also important reservoirs for groundwater, and host important deposits of copper, uranium, lead, zinc, as well as gold and diamonds.



MAJOR CONCEPTS

1. Sedimentary rocks form at Earth's surface by the hydrologic system. Their origin involves the weathering of preexisting rock, transportation of the material away from the original site, deposition of the eroded material in the sea or in some other sedimentary environment, followed by compaction and cementation.
2. Two main types of sedimentary rocks are recognized: (a) clastic rocks and (b) chemically precipitated rocks, including biochemical rocks.
3. Stratification is the most significant sedimentary structure. Other important structures include cross-bedding, graded bedding, ripple marks, and mud cracks.
4. The major sedimentary systems are (a) fluvial, (b) alluvial-fan, (c) eolian, (d) glacier, (e) delta, (f) shoreline, (g) organic-reef, (h) shallow-marine, (i) submarine fan, and (j) deep-marine.
5. Sedimentary rock layers can be grouped into formations, and formations can be grouped into sequences that are bound by erosion surfaces. These formations and sequences form an important interpretive element in the rock record.
6. Plate tectonics controls sedimentary systems by creating uplifted source areas, shaping depositional basins, and moving continents into different climate zones.

THE NATURE OF SEDIMENTARY ROCKS

Sedimentary rocks form from fragments derived from other rocks and by precipitation from water. They typically occur in layers, or strata, separated one from the other by bedding planes and differences in composition.

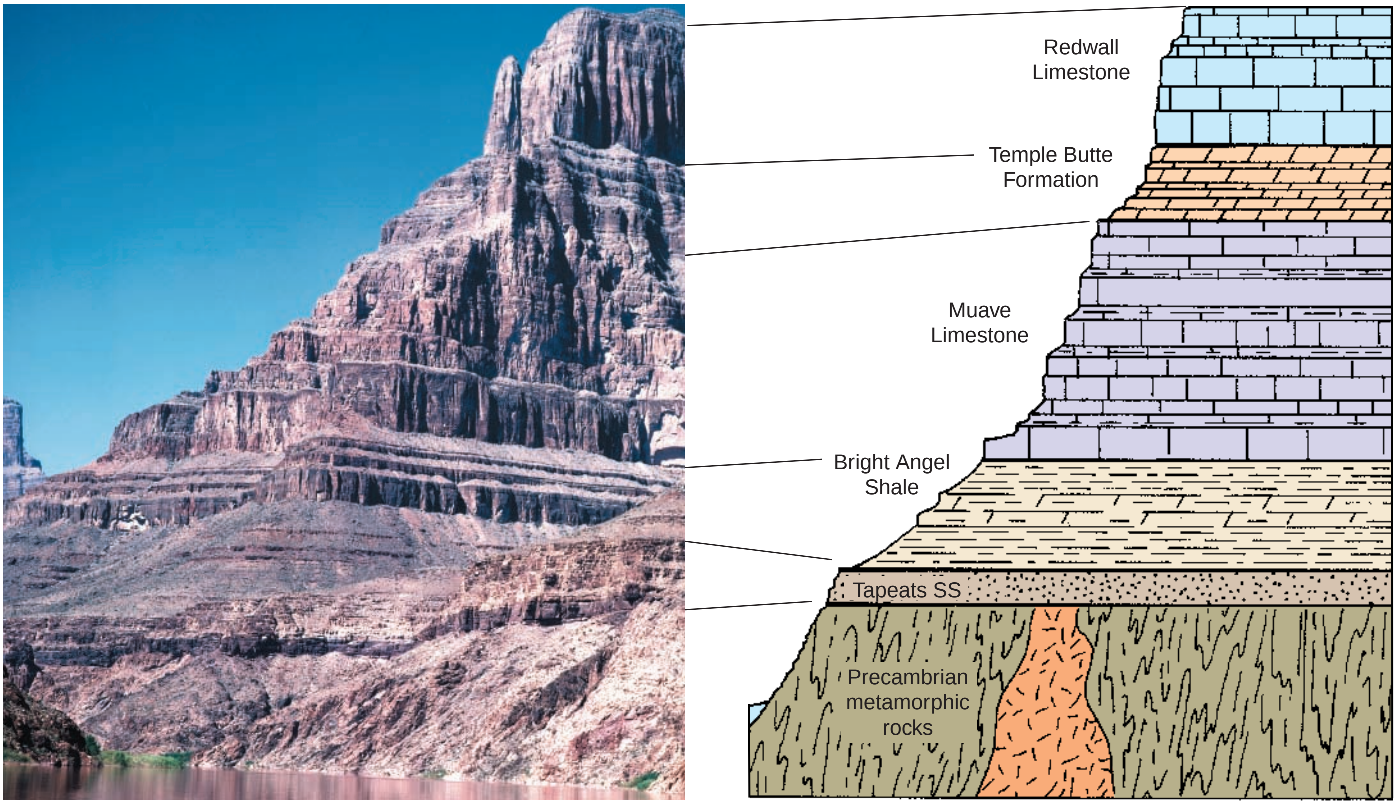
Sedimentary rocks are probably more familiar than the other major rock types. Few people, however, are aware of the true nature and extent of sedimentary rock bodies.

The constituents of sedimentary rocks are derived from the mechanical breakdown and chemical decay of preexisting rocks. This **sediment** is compacted and cemented to form solid rock bodies. The original sediment can be composed of various substances:

1. Fragments of other rocks and minerals, such as gravel in a river channel, sand on a beach, or mud in the ocean
2. Chemical precipitates, such as salt in a saline lake or gypsum in a shallow sea
3. Organic materials formed by biochemical processes, such as vegetation in a swamp, coral reefs, and calcium carbonate precipitated by in the ocean

Sedimentary rocks are important because they preserve a record of ancient landscapes, climates, and mountain ranges, as well as the history of the erosion of Earth. In addition, fossils are found in abundance in sedimentary rocks younger than 600 million years and provide evidence of the evolution of life through time. Earth's geologic time scale was worked out using this record of sedimentary rocks and fossils.

An excellent place to study the nature of sedimentary rocks is Arizona's Grand Canyon (Figure 5.1), where many distinguishing features are well exposed. Their most obvious characteristic is that they occur in distinct layers, or **strata** (singular **stratum**), many of which are more than 100 m thick. Rock types that are resistant to weathering and erosion form cliffs, and nonresistant rocks erode into gentle slopes. From Figure 5.1, you should be able to recognize the major layers or **formations** in the geologic cross section shown in the diagram. The formations exposed in the Grand Canyon can be traced across much of northern Arizona and parts of adjacent states. In fact, they cover an area of more than 250,000 km^2. A close view



(A) Formations that are resistant to weathering and erosion (such as sandstone and limestone) erode into vertical cliffs. Rocks that weather easily (such as shale) form slopes or terraces.

(B) A cross section of the Grand Canyon graphically illustrates the major sedimentary formations. The sedimentary strata are essentially horizontal and were deposited on older igneous and metamorphic rocks.

FIGURE 5.1 **The layered series of sedimentary rocks exposed in the Grand Canyon, Arizona,** is almost 2000 m thick and was deposited over a period of 300 million years. A similar sequence of sedimentary rocks occurs through the stable platforms of most continents.

of sedimentary rocks in the canyon reveals that each formation has a distinctive texture, composition, and internal structure.

The major layers of the sandstone, limestone, and shale actually consist of smaller units separated by **bedding planes** that are marked by some change in composition, grain size, or color, or by other physical features. Animal and plant **fossils** are common in most of the rock units and can be preserved in great detail (Figure 5.2). The term *fossil* is generally used to refer to any evidence of former life (plant or animal). It may be direct evidence, such as shells, bones, or teeth, or it may be indirect, such as tracks and burrows produced by organic activity. The texture of most sedimentary rocks consists of mineral grains or rock fragments that show evidence of abrasion (Figure 5.2B) or consist of interlocking grains of the minerals calcite or dolomite. In addition, many layers show ripple marks (Figure 5.2C), mud cracks (Figure 5.2D), and other evidence of water deposition preserved in the bedding planes. All of these features show that sedimentary rocks form at Earth's surface in environments similar to those of present-day deltas, streams, beaches, tidal flats, lagoons, and shallow seas.

Sedimentary rocks are widespread on the continents, covering about 75% of the surface of the continents; they therefore form most of the landscape. Nearly 100% of the ocean floor is blanketed with at least a thin layer of sediment. The map in Figure 5.3 illustrates the distribution of sedimentary rocks in North America. You can see that the stable platform of the Great Plains and adjacent areas is completely covered by a relatively thin layer of sedimentary rocks. Most of these layers of rock are nearly horizontal. In addition, folded layers of sedimentary rocks are exposed in mountain belts. Sedimentary rocks are rare in the Canadian shield.

(A) Fossils found in sedimentary rocks include representatives of most types of marine animals.

(B) A microscopic view of sand grains in sediment shows the effects of transportation by running water. The grains are rounded and sorted to approximately the same size.

(C) Ripple marks preserved in sandstone suggest that the sediment was deposited by the current action of wind or water.

(D) Mud cracks form where sediment dries while it is temporarily exposed to the air. This structure is common on tidal flats, in shallow lake beds, and on stream banks.

FIGURE 5.2 **A variety of features in sedimentary rocks** show their origin at Earth's surface as a result of the hydrologic system. These include stratification, cross-bedding, ripple marks, mud cracks, fossils, and other features formed at the time the sediment was deposited.

TYPES OF SEDIMENTARY ROCKS

Sedimentary rocks are classified on the basis of the texture and composition of their constituent particles. Two main groups are recognized: (1) clastic rocks, formed from fragments of other rocks, and (2) chemical rocks and biochemical rocks.

Clastic Sedimentary Rocks

How are the different types of sedimentary rocks distinguished and classified?

One important category of sedimentary rock consists of particles of gravel, sand, or mud. Rocks made up of such fragmental material are called clastic rocks. The term **clastic** comes from the Greek word *klastos,* meaning "broken," and describes the broken and worn particles of rock and minerals that were carried to the sites of deposition by streams, wind, glaciers, and marine currents.

FIGURE 5.3 **Sedimentary rocks in North America** are widespread in the stable platforms. They are also found as deformed layers in the folded mountain belts. In the stable platform, the sedimentary sequence is generally less than 2 km thick. In folded mountain belts and on continental margins, they may be much thicker.

In general, clastic rocks are subdivided according to grain size (Figure 5.4). From the largest grain size to the smallest, the types of clastic rocks are conglomerate, sandstone, and mudrock. The grain size of clastic sedimentary rocks is not controlled by progressive growth of grains as in igneous rocks, but is instead controlled by the size of clasts present in the source and by the carrying capacity of the transporting medium—a river, a glacier, or the wind. Grains are deposited when the transporting medium loses its carrying capacity, commonly when its velocity decreases. Thus, sediment deposited from a fast-moving stream is coarser than that deposited in a quiet lagoon.

In what way are clastic sedimentary rocks different from chemical precipitates?

Conglomerate consists of consolidated deposits of gravel (fragments larger than 2 mm in diameter) with various amounts of sand and mud in the spaces between the larger grains (Figure 5.5A). The gravel is usually smooth and well rounded, suggesting the grains were rounded during transport. Most conglomerates are only crudely stratified and include beds and lenses of sandstone. High enery is required to transport large clasts like gravel, so conglomerate tends to be deposited in high-energy environments where water is flowing rapidly. Conglomerate accumulates today at the bases of many mountain ranges, in stream channels, and on some beaches.

Sandstone is probably the most familiar, though not the most abundant, sedimentary rock because it is well exposed, easily recognized, and generally resistant to weathering (Figure 5.5B). The sand grains range from 0.0625 to 2 mm in diameter and can be composed of almost any material, so sandstones can be

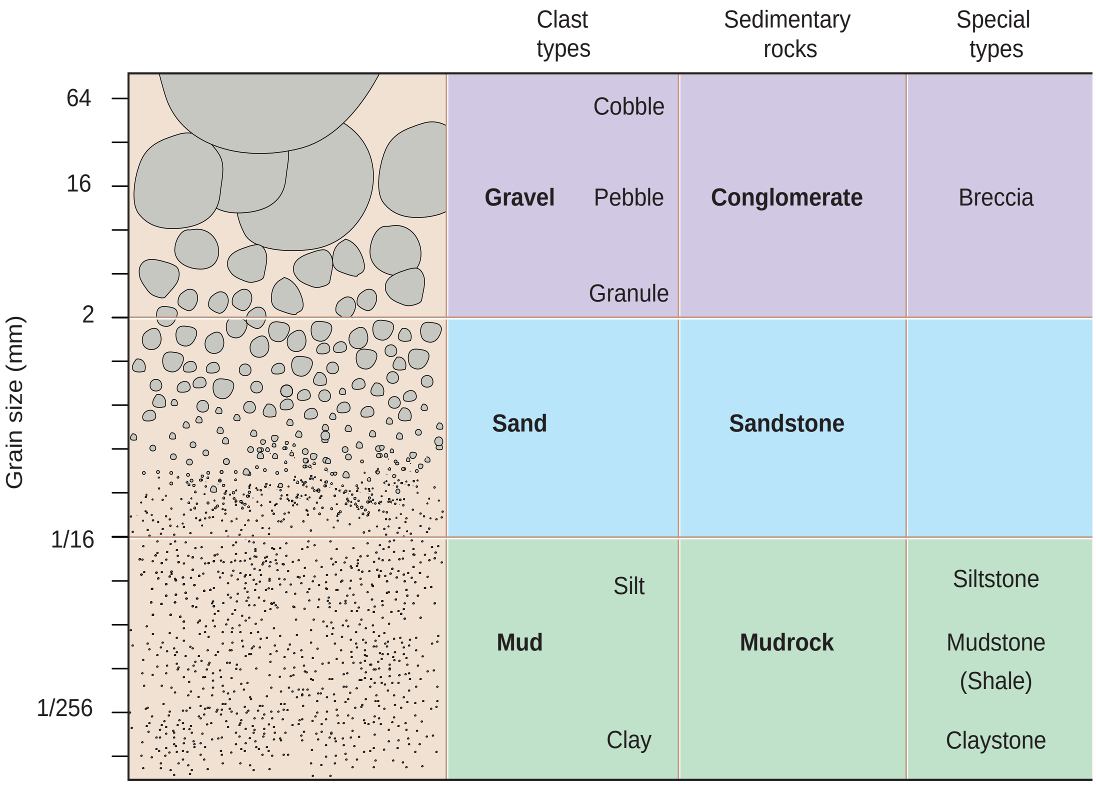


FIGURE 5.4 **The classification of common clastic sedimentary rocks** is based primarily on grain size and secondarily on textural and compositional variations.

almost any color. Quartz grains (Figure 5.2B), however, are usually most abundant because quartz is a common constituent in many other rock types and because it is resistant to abrasion or chemical breakdown as the sediment particles are transported. The particles of sand in most sandstones are cemented by calcite, quartz, or iron oxide. Other grains maybe feldspar (in a rock called arkose), pieces of chert, or small rock fragments.

The composition of a sandstone provides an important clue to its history. During prolonged transportation, small rock fragments and minerals that readily decompose such as olivine, feldspar, and mica break down into finer particles and are winnowed out, leaving only the stable quartz. Clean, well-sorted sandstone composed of well-rounded quartz grains indicates prolonged transportation, or even several cycles of erosion and deposition.

Mudrocks are fine-grained clastic rocks with grains less than 1/16 mm (0.0625 mm) across (Figure 5.4). Mudrocks are the most abundant sedimentary rocks. They are usually soft and weather rapidly to form slopes, so relatively few fresh, unweathered exposures are found. They are frequently deposited in river floodplains and deltas and other shallow marine settings. Many mudrocks also show evidence of burrowing by organisms.

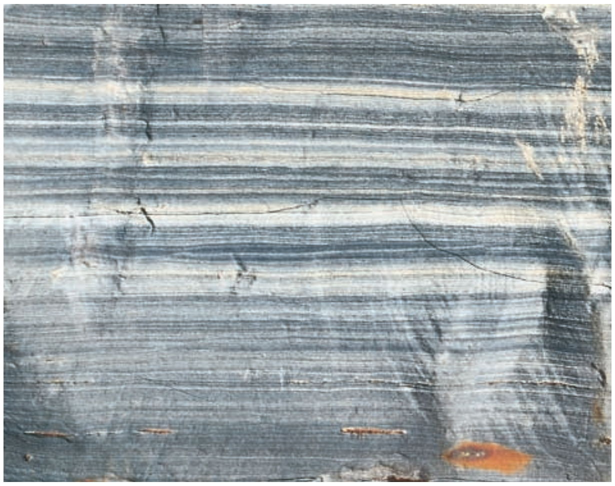
What rock types commonly form in shallow-marine environments?

There are several important varieties of mudrocks. **Siltstone** is a fine-grained clastic rock coarser than **claystone.** Clasts in mudrocks tend to be more angular than those in sandstone. Many of the small clasts, especially in claystones, are flaky minerals like mica and clay. Tiny grains of quartz are another major constituent. A mudrock that contains very thin layers (**laminae**) is called **shale** (Figure 5.5C). Shales split easily along these layers to form small paper-thin sheets or flakes. The particles in claystones are generally too small to be clearly seen and identified even under a microscope.

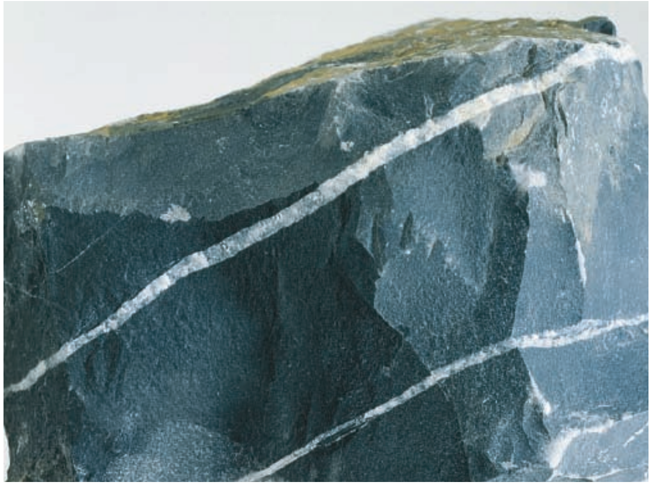
Many shales are black and rich in organic material that accumulated in a variety of quiet-water, low-oxygen environments, such as lagoons and seas with

(A) Conglomerate is a coarse-grained clastic sedimentary rock.

(B) Sandstone is a clastic sedimentary rock composed of sand-sized particles.



(C) Shale is a clastic sedimentary rock composed of very fine grains of clay or mud.



(D) Limestone is the most common nonclastic sedimentary rock. It is composed mostly of calcium carbonate.

(E) Limestone may also be made of abundant shell fragments.

(F) Gypsum precipitates as shallow bodies of water evaporate.

Figure 5.5 **Major types of sedimentary rocks.** Clastic rocks are shown on the left and biochemical chemical precipitates on the right. All of the rocks are shown at actual size.

poor circulation where oxygen-poor water accumulated. Red shales are colored with iron oxide and suggest oxidizing conditions in the environments in which they accumulate, such as river floodplains, tidal flats, lakes, and well-mixed oceans.

Biochemical and Chemical Sedimentary Rocks

The other major category of sedimentary rocks form when chemical processes remove ions dissolved in water to make solid particles. Some are **biochemical rocks** with sediment formed during the growth of organisms such as algae, coral, or swamp vegetation. Others are inorganic **chemical precipitates** from lakes or shallow seas.

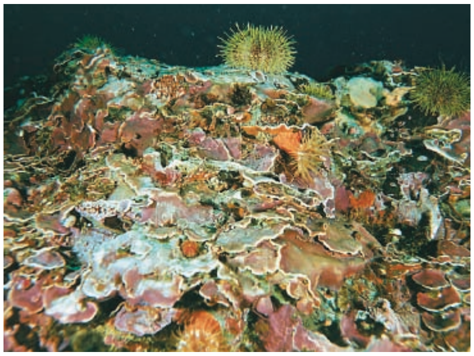
Limestone is by far the most abundant chemically precipitated rock (Figure 5.5D). It is composed principally of calcium carbonate ($CaCO_3$—dominantly calcite) and originates by both inorganic chemical and biochemical processes. Indeed, the distinction between biochemical and chemical rocks is rarely clear cut. Limestones have a great variety of rock textures, and many different types have been classified. Three important examples are described here: skeletal limestone, oolitic limestone, and microcrystalline limestone.

How do organisms make sedimentary rocks?

Some marine invertebrate animals construct their shells or hard parts by extracting calcium and carbonate ions from seawater. Corals, clams, algae, snails,and many other marine organisms construct their skeletons of calcium carbonate. After the organisms die, the shells accumulate on the seafloor. Over a long period of time, they build up a deposit of limestone with a texture consisting of shells and shell fragments (Figure 5.5E). These particles may then be cemented together as more calcite precipitates between the grains. This type of limestone, composed mostly of skeletal debris, can be several hundred meters thick and can extend over thousands of square kilometers. **Chalk**, for example, is a skeletal limestone in which the skeletal fragments are remains of microscopic plants and animals.

Other limestones are composed of small semispherical grains of calcium carbonate known as **oolites.** Oolites form where small fragments of shells or other tiny grains become coated with successive thin layers of $CaCO_3$ as they are rolled along the seafloor by waves and currents.

A third important type of limestone forms in quiet waters where calcium carbonate is precipitated by algae as tiny, needlelike crystals that accumulate on the seafloor as limy mud (Figure 5.6A). Soon after deposition, the grains commonly are modified by compaction and recrystallization. This modification produces



(A) Some kinds of algae produce calcium carbonate particles that accumulate to form limestone. These are found near the Kuril Islands of the north Pacific. Each leaflike structure is about 5 cm across.

(B) Diatoms are the shells of tiny single-celled algae that are made of silica. Some deep-marine sediments are dominated by diatoms like these seen through a microscope. Accumulations convert to chert.

FIGURE 5.6 **Algae** are important biochemical factories for the generation of sediment. *[(a) Mikhail V. Propp/Peter Arnold, Inc.; (b) Dr. Darlyne A. Murawski/NGS Image Collection]*

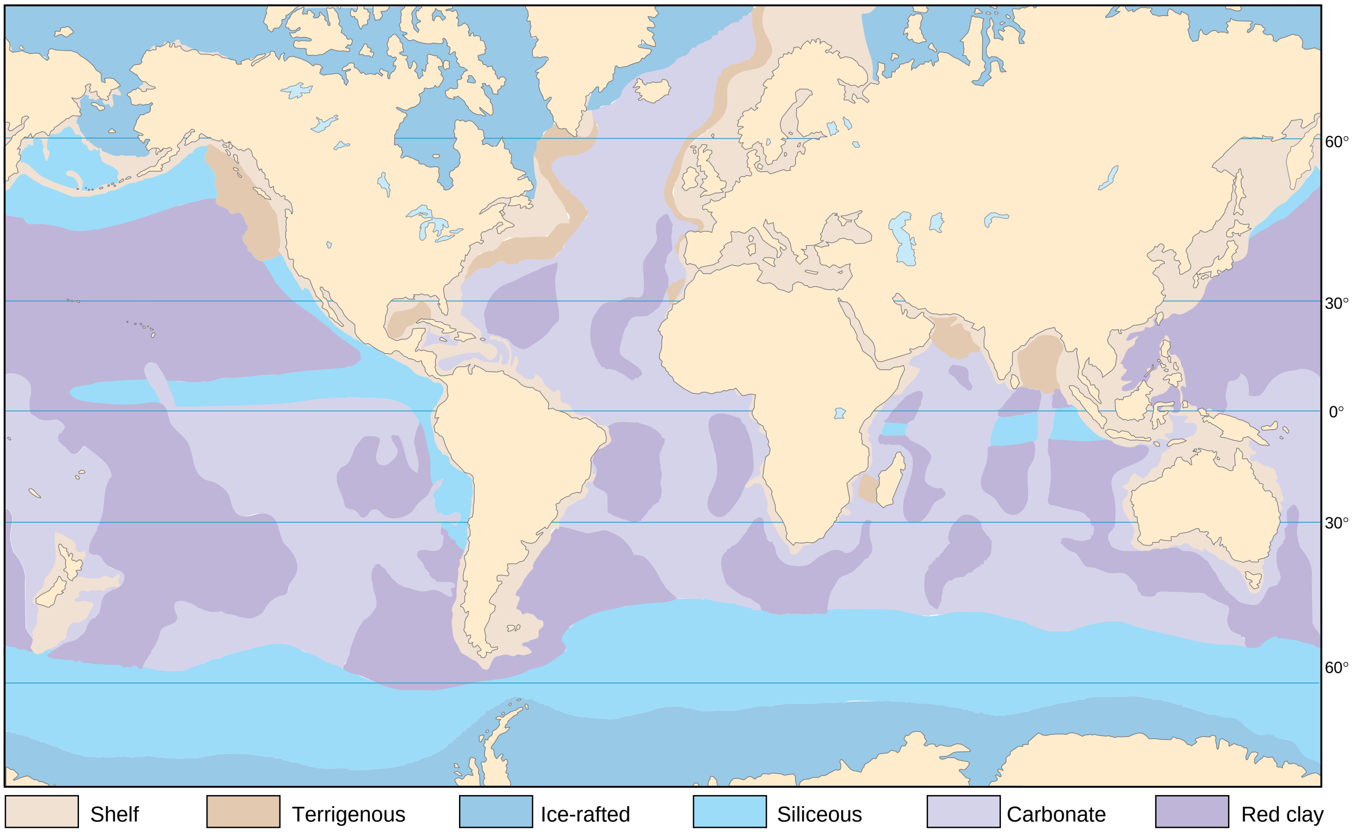


FIGURE 5.7 **Marine sediments** form largely by biochemical precipitation. Carbonate sediments dominate at shallow depths and in warm near-shore waters. Elsewhere, siliceous sediment, which eventually forms chert, is typical in deeper water. Most of the red clay is transported from the continents as wind-blown dust.

microcrystalline limestone (or micrite), a rock with a dense, very fine-grained texture (Figure 5.5D). Its individual crystals can be seen only under high magnification. Other types of carbonate grains may be cemented together by microcrystalline limestone.

Inorganic limestone also is precipitated from springs and from the dripping water in caves to form beautifully layered rocks called travertine.

Most limestone forms on the shallow continental shelves where waters are warm and organic production is high. In contrast, carbonate sediments are rare in deep water and do not accumulate on the abyssal plains. In fact, calcite is not stable at the low temperatures and high pressures found on the deep seafloor. Calcite shells formed in surface waters fall toward the seafloor when the organism dies; but in deep water, calcite shells dissolve before they reach the bottom. Near the equator, calcite is not stable at depths below about 4,500 m. Where the seafloor is shallower than this, as on oceanic ridges, carbonate sediment will accumulate (Figure 5.7).

Dolostone is a carbonate rock composed of the mineral dolomite, a calcium-magnesium carbonate $CaMg(CO_3)_2$. It is similar to limestone in general appearance, but reacts with acid only when powdered. Dolostone is commonly dull brownish yellow or light gray. It can develop by direct precipitation from seawater, but such environments are extremely rare. Instead, dolostone may form by the reaction of magnesium-bearing groundwater with calcium carbonate in limestone. The recrystallization generally destroys the original texture of the rock. In a fashion, dolostones are chemical precipitates formed from biochemical rocks.

What kind of sedimentary rock typically forms on the deep-ocean floor?

Chert is a common rock composed of microcrystalline quartz. In a hand specimen, it is hard, dense, and typically breaks like glass, but under a high-power microscope, it has a fibrous or granular texture. Chert is usually white or shades

FIGURE 5.8 **Coal** is an important biochemical precipitate. It forms by the decomposition of organic material buried within sedimentary rocks. Lush vegetation may form in an ancient swamp and then be converted by burial into coal. The coal beds on the left are interlayered with sandstone.

of gray, tan, green, or red. Several varieties are recognized on the basis of color, including flint (black) and jasper (red). Because it fractures to make sharp edges, it has been shaped by many ancient people to make arrowheads, spear points, and tools. Chert commonly occurs as irregular nodules in limestone or as distinct thin layers in marine sedimentary rocks. Some nodular chert precipitates from pore fluids, particularly in carbonate rocks. However, most chert probably forms biochemically.

A distinctive type of deep-marine chert develops from deposits of siliceous shells of microscopic organisms, such as radiolaria and diatoms (Figure 5.6B). In the modern ocean, this kind of thinly bedded sediment dominates deep-marine environments where these tiny shells rain onto the seafloor. Siliceous marine sediment is thickest beneath regions of high biologic productivity. Compare the map of the biosphere (Figure 1.4) with the distribution of deep-marine chert (siliceous sediment in Figure 5.7), and you will discover that the siliceous sediment dominates in regions of high biologic productivity—continental margins, in near-polar seas, and along the equator. Carbonate minerals do not accumulate on the seafloor where the ocean is very deep because calcite is not stable at great depths (Figure 5.7). If the water is deep enough, a falling shell made of carbonate is dissolved back into the seawater.

Another important biochemical component of many sedimentary rocks are hydrocarbons or organic compounds derived from living things. The decay of these materials at in deeply buried sedimentary rocks produces oil, natural gas, and coal (Figure 5.8).

Only a few important rock types form strictly by inorganic processes. **Rock salt** is made of the mineral halite (NaCl). It crystallizes when evaporation concentrates sodium and chlorine ions to the point that salt is stable in the residual brine. Strong evaporation creates saline lakes in closed desert basins (for example, the Great Salt Lake and the Dead Sea). Enhanced evaporation also occurs in restricted bays along the shore of the ocean. **Gypsum,** $CaSO_4{\cdot}2H_2O$, also originates from evaporation. It collects in layers as calcium sulfate is precipitated (Figure 5.5F) from water. Because **evaporites** (rocks formed by evaporation) accumulate only in restricted basins subjected to prolonged evaporation, they are important indicators of ancient climatic and geographic conditions.

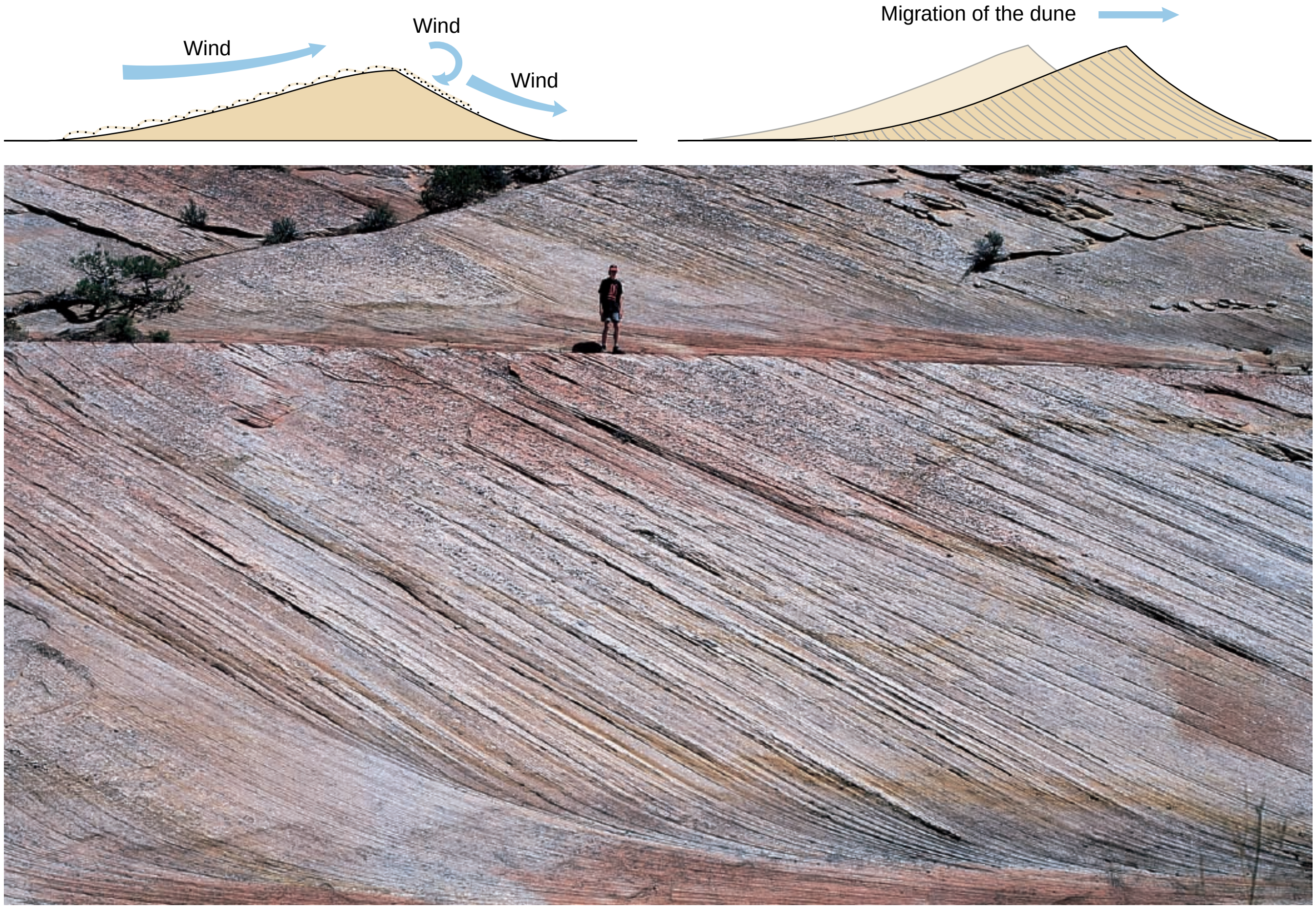


FIGURE 5.9 **Cross-bedding** is formed by the migration of sand waves (ripple marks or dunes). Particles of sediment, carried by currents, travel up and over the sand wave and are deposited on the steep downcurrent face to form inclined layers.

SEDIMENTARY STRUCTURES

Sedimentary rocks commonly show layering and other structures that form as sediment is transported. The most important sedimentary structures are stratification, cross-bedding, graded bedding, ripple marks, and mud cracks. Primary sedimentary structures provide key information about the conditions under which the sediment accumulated.

Stratification

Why are sedimentary structures important in the study of sedimentary rocks?

One of the most obvious characteristics of sedimentary rocks is that they occur in distinct layers expressed by changes in color, texture, and the way the different rock units weather and erode. These layers are termed strata, or simply **beds.** The planes separating the layers are planes of stratification, or bedding planes. **Stratification** occurs on many scales and reflects the changes that occur during the formation of a sedimentary rock. Large-scale stratification is expressed by major changes in rock types (**formations**) (Figure 5.1). For example, cliffs of limestone or sandstone can alternate with slopes of weaker shale.

The origin of stratification is quite simple. Different layers form because of some change that occurs during the process of deposition. But there are many types of changes that occur and operate on many different scales, so the construction of a detailed history of sedimentary rocks presents a real challenge to geologists. Changes in weather, changes in the seasons, and changes in climate all can produce stratification in a sedimentary basin. Tectonic changes such as uplift and subsidence of the continental platform, mountain building, and volcanism all produce changes in material transported to the sea, and all can produce different layers of sedimentary rock.

Cross-Bedding

Cross-bedding is a type of stratification in which the layers within a bed are inclined at an angle to the upper and lower surfaces of the bed. The formation of cross-bedding is shown in Figure 5.9. As sand grains are moved by wind or water, they form small ripples or large **dunes.** These **sand waves** range in scale from small ripples less than a centimeter high to giant sand dunes several hundred meters high. Typically, they are asymmetrical, with the gentle slope facing the moving current. As the particles migrate up and over the sand wave, they accumulate on the steep downcurrent face and form inclined layers. The direction of flow of the ancient currents that formed a given set of cross-strata can be determined by measuring the direction in which the strata are inclined. We can determine the patterns of ancient current systems by mapping the direction of cross-bedding in sedimentary rocks. Moreover, the style of cross-bedding changes with the sediment supply and with the flow conditions at the depositional site. Thus, the details of an ancient environment can be interpreted from careful study of the type of cross-bedding.

Graded Bedding

What sedimentary structure forms from a turbidity current?

Another distinctive type of stratification, called **graded bedding,** displays a progressive decrease in grain size upward through a bed (Figure 5.10). This type of stratification commonly is produced on the deep-ocean floor by **turbidity currents,** which transport sediment from the continental slope to adjacent deep ocean forming bodies of rock called **turbidites.** A turbidity current is generated by turbid (muddy) water, which, being denser than the surrounding clear water, sinks beneath it and moves rapidly down the continental slope (Figure 5.11). The denser, muddy water moves out along the bottom of the basin and can flow for a considerable distance, even along the flat surface of an abyssal floor. As a turbidity current moves across the flat floor of a basin, its velocity at any given point

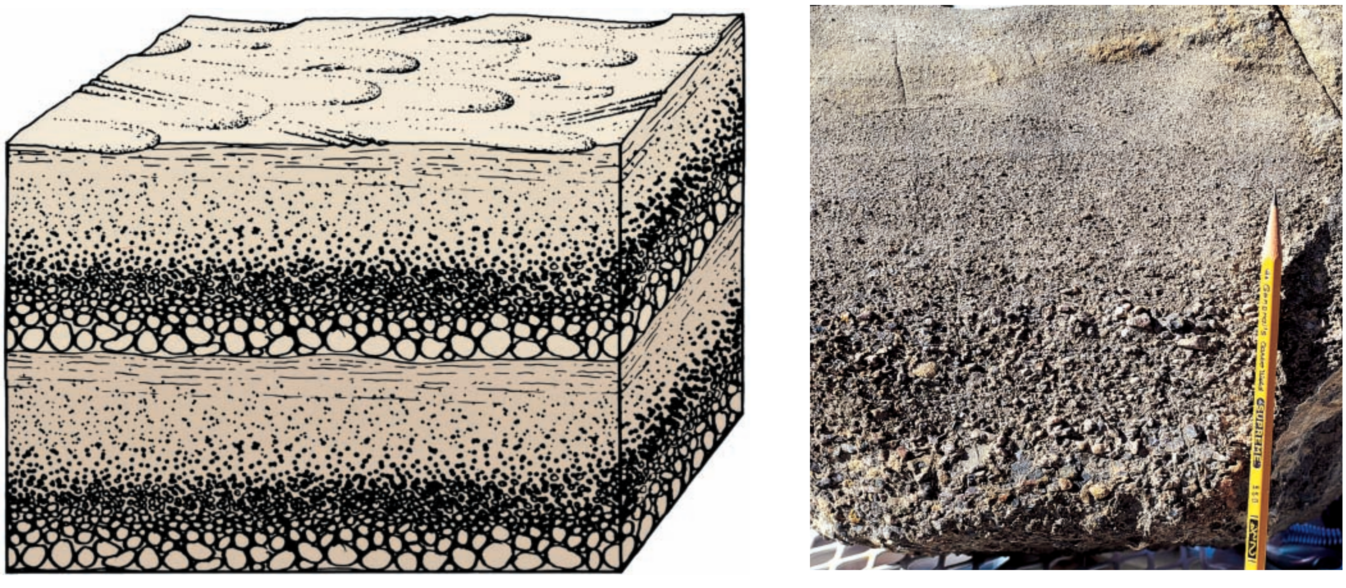


Figure 5.10 **Graded bedding** is produced by turbidity currents. It occurs in widespread layers, each layer generally less than a meter thick. Slumps off the deep continental slopes commonly produce great thicknesses of graded layers, which can easily be distinguished from sediment deposited in most other environments.

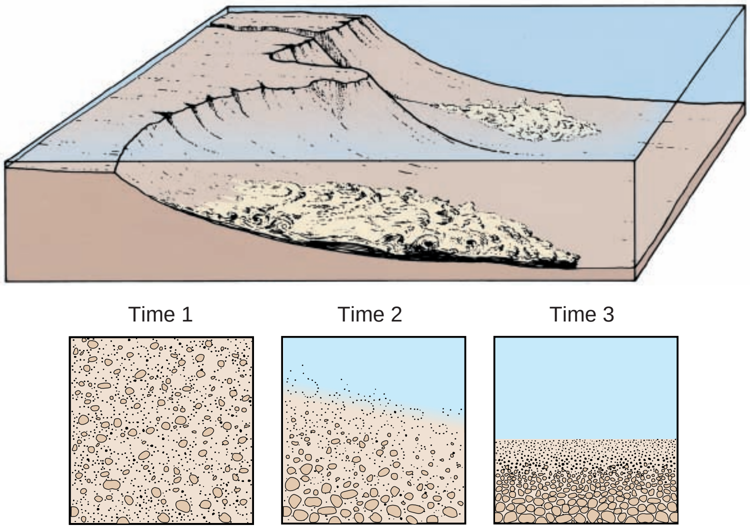


FIGURE 5.11 **The movement of turbidity** currents down the slope of the continental shelf can be initiated by a landslide or an earthquake. Sediment is moved largely in suspension. As the current slows, the coarse grains are deposited first, followed by the deposition of successively finer-grained sediment. Fine mud slowly settle out from suspension after the turbidity current stops. A layer of graded bedding is thus produced from a single turbidity current.

gradually decreases. The coarsest sediment in the turbidity current is deposited first, followed by successively smaller particles. After the turbid water ceases to move, the sediment remaining suspended in the water gradually settles out. One turbidity current, therefore, deposits a single layer of sediment, which exhibits a continuous gradation from coarse material at the base to fine material at the top. Subsequent turbidity currents can deposit more layers of graded sediment, with sharp contacts between layers. The result is a succession of widespread, nearly horizontal turbidites, each a graded unit deposited by a single turbidity current. Turbidity currents also form where streams discharge muddy water into a clear lake or reservoir (Figure 5.12).

Small turbidity currents can be created by pouring muddy water down the side of a tank filled with clear water. The mass of muddy water moves down the slope of the tank and across the bottom at a relatively high speed, without mixing with the clear water.

Turbidity currents are commonly generated by earthquakes or submarine landslides, during which mud, sand, and even gravel are transported downslope. In 1929 one of the best-documented large-scale turbidity currents was triggered by an earthquake near the Grand Banks, off Newfoundland. Slumping of a large mass of soft sediment (estimated to be 100 km^3) moved as a turbidity current down the continental slope and onto the abyssal plain, eventually covering an area of 100,000 km^2. As the turbidity current moved downslope, it broke a series of transatlantic cables at different times. The speed of the current, determined from the intervals between the times when the cables broke, was from 80 to 95 km/hr. This mass of muddy water formed a graded layer of sediment over a large area of the Atlantic floor.

Ripple Marks, Mud Cracks, and Other Surface Impressions

Ripple marks are commonly seen in modern streambeds, in tidal flats, and along the shores of lakes and the sea. Many are preserved in rocks and provide information concerning the environment of deposition, such as depth of water, ancient current directions, and trends of ancient shorelines (Figure 5.2C). **Mud cracks** are also commonly preserved in sedimentary rock and show that the sedimentary environment was occasionally exposed to the air during deposition. Mud cracks in

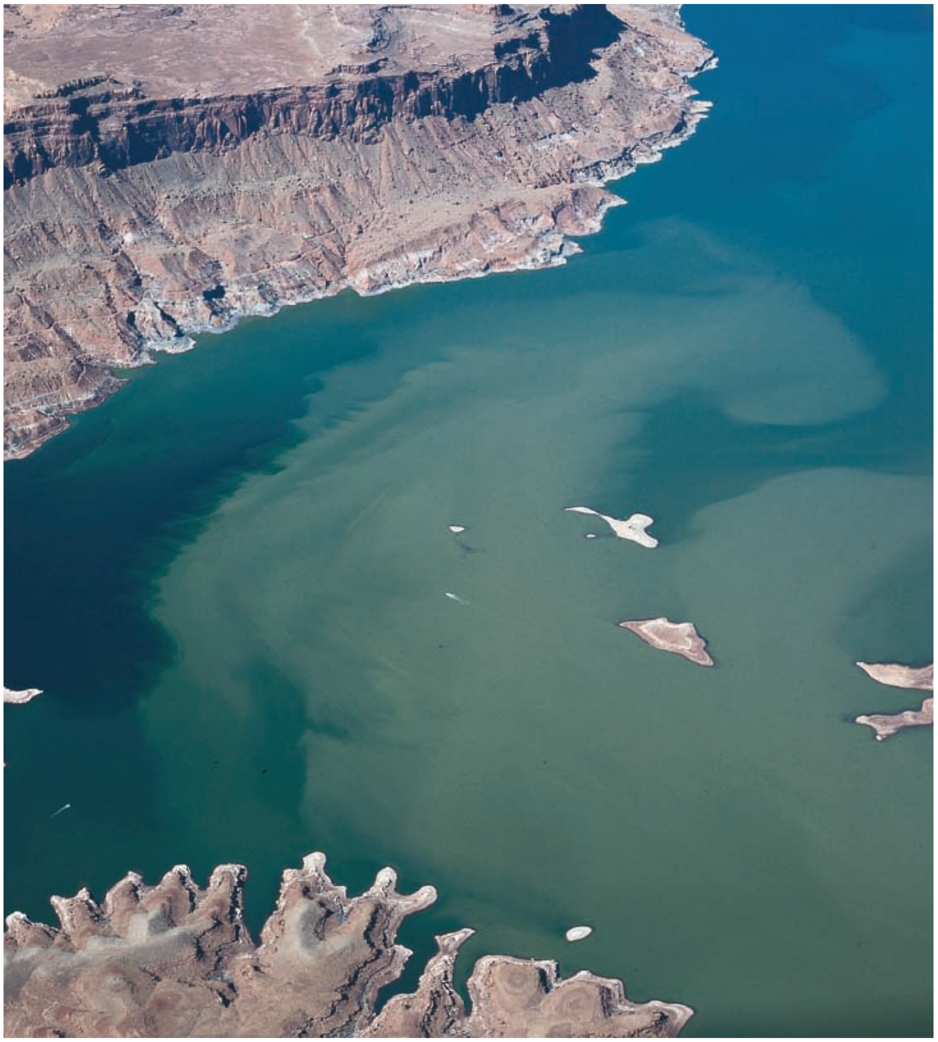


FIGURE 5.12 **Turbidity currents** into Lake Powell, Utah, result where the muddy water of the Colorado River enters the clear water of the lake.

rocks suggest that the original sediment was deposited in shallow lakes, on tidal flats, or on exposed stream banks (Figure 5.2D). Rain prints are even preserved in some mudrocks.

Fossils and Trace Fossils

Another key feature of many sedimentary rocks are fossils of once living organisms (Figure 5.2A). Fossils often reveal much about the past environment, giving us hints about whether a deposit is marine or continental, what the water depth was when the sediment was deposited, and about temperature and salinity of the water. Beyond that, however, fossils in sedimentary rocks reveal the history of the evolution of life. Although the record is far from complete, everything we know about past life comes from reconstructions based on ancient fossils.

Tracks, trails, and borings of animals are typically associated with ripple marks and mud cracks and can provide additional important clues about the environment in which the sediment accumulated.

As can be seen, primary sedimentary structures and fossils are the clues or the tools used by geologists to interpret the conditions and environment at the site where the sediment is deposited.

SEDIMENTARY SYSTEMS

Weathering of preexisting rocks, transportation, and deposition, followed by compaction and cementation, are the major steps in the formation of sedimentary rocks. The major sedimentary systems are (1) fluvial, (2) alluvial-fan, (3) eolian, (4) glacial, (5) delta, (6) shoreline, (7) organic-reef, (8) shallow-marine, and (9) deep-marine. Each of these systems has a specific set of physical, chemical, and biological conditions and therefore develops distinctive rock types and fossil assemblages.

Sedimentary Systems

Sedimentary systems operate at Earth's surface through interactions of the hydrologic system and the crust. As a result of the transfer of energy between the various parts of a sedimentary system, new landforms and new bodies of sedimentary rock are created. Most the energy that drives these systems ultimately comes from the Sun; gravitational and chemical potential energy are also transferred in various parts of the sedimentary system. It is useful to visualize a hypothetical sedimentary system as consisting of a source of sediment (weathering), a transport path for the sediment, a site of deposition, and the processes that compact and cement the sediment together to form a solid rock. Fortunately, many of these sedimentary processes operate today, and geologists actively study rivers, deltas, and oceans and other sedimentary systems in an effort to understand the characteristics of rocks formed in these environments.

Weathering

Weathering is the interaction between the elements in the atmosphere and the rocks exposed at Earth's surface. The atmosphere can mechanically break down the rock through processes such as ice wedging, and it can chemically decompose the rock by a variety of reactions. We will study the details of weathering in Chapter 10. For now, note that weathering is the first step in the genesis of sedimentary rock. The atmosphere breaks down and decomposes preexisting solid rock and forms a layer of loose, decayed rock debris, or soil. This unconsolidated material can then be transported easily by water, wind, and glacial ice.

Transportation

Running water is the most effective form of sediment transport. All rivers carry large quantities of sediment toward the sea. This fact is readily appreciated if you consider the great deltas of the world, each formed from sediment transported by a river (Figure 5.13; see also Figure 12.38). Indeed, sediment is so abundant in most rivers that a river might best be thought of as a system of water and sediment rather than simply a channel of flowing water.

As clastic sediment is transported by a river, it is sorted and separated according to grain size and composition. Large particles accumulate in high-energy environments as gravel, medium-sized grains are concentrated as sand, and finer material settles out as mud. The grain size of the sediment correlates with the energy of the transporting medium. Thus, large particles are carried by rapidly moving streams with high amounts of kinetic energy; only small particles are transported by slowly moving streams. Wind, glaciers, and shoreline currents also transport sediment, but their activity is somewhat restricted to special climate zones. Components from dissolved minerals are carried in solution and are ultimately precipitated to form limestone or salt, for example.

Deposition

Probably the most significant factor in the genesis of sedimentary rocks is the place where the sediment is deposited. The idealized diagram in Figure 5.13

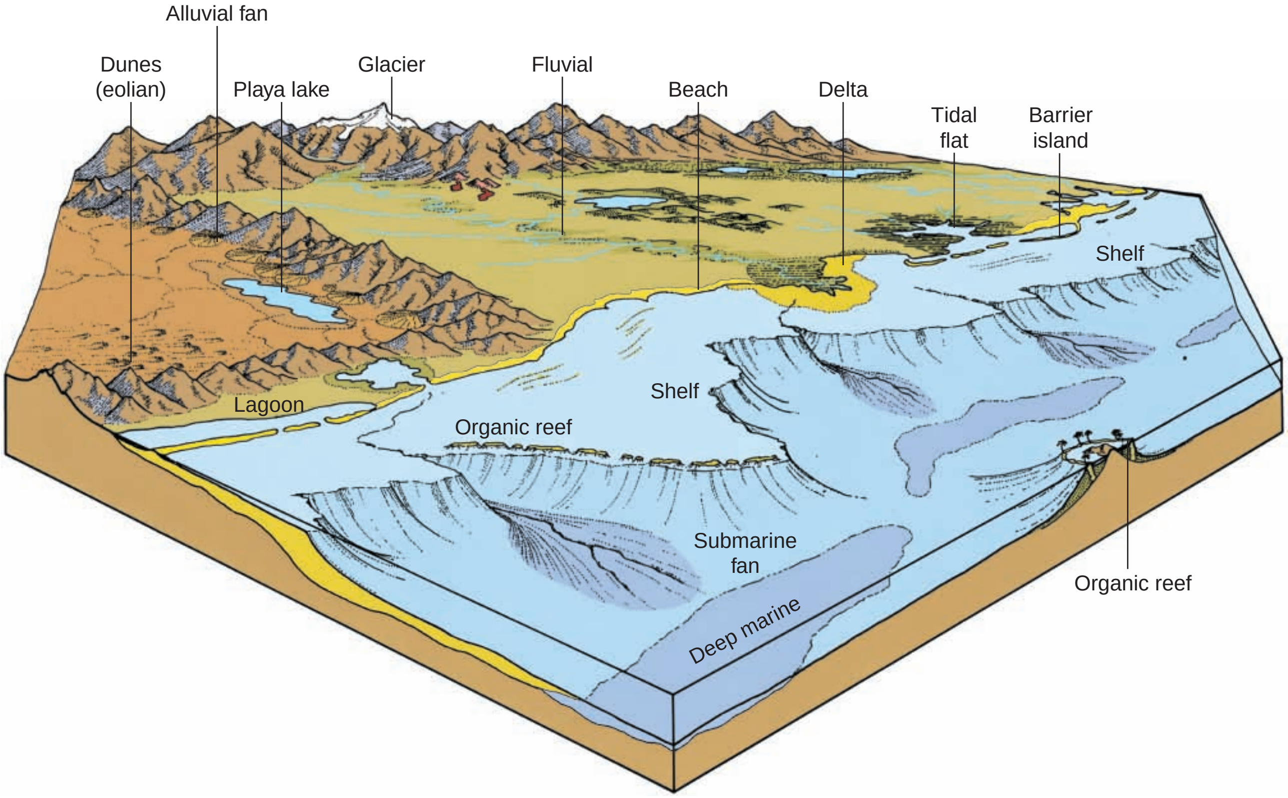


FIGURE 5.13 **The major sedimentary systems** are represented in this idealized diagram. Most sediment moves downslope from continental highlands toward the oceans, so the most important sedimentary systems are found along the shores and in the shallow seas beyond. Sedimentary systems can be categorized in three groups: continental, shoreline (transitional), and marine. Their important characteristics and the types of sediments that accumulate in each are outlined in Figures 5.14 to 5.25.

shows the major depositional systems. The most important continental systems are river (**fluvial**) systems, **alluvial fans,** desert dunes, and margins of **glaciers.** Marine systems include the **shallow marine,** which cover parts of the continental platform, **reefs, submarine fans,** and the floors of the **deep-ocean basins.** Between continental areas and marine areas are the transitional, or mixed, environments that occur along the coasts and are influenced by both marine and nonmarine processes. These include **deltas, beaches, barrier islands, tidal flats,** and **lagoons** (Figure 5.13).

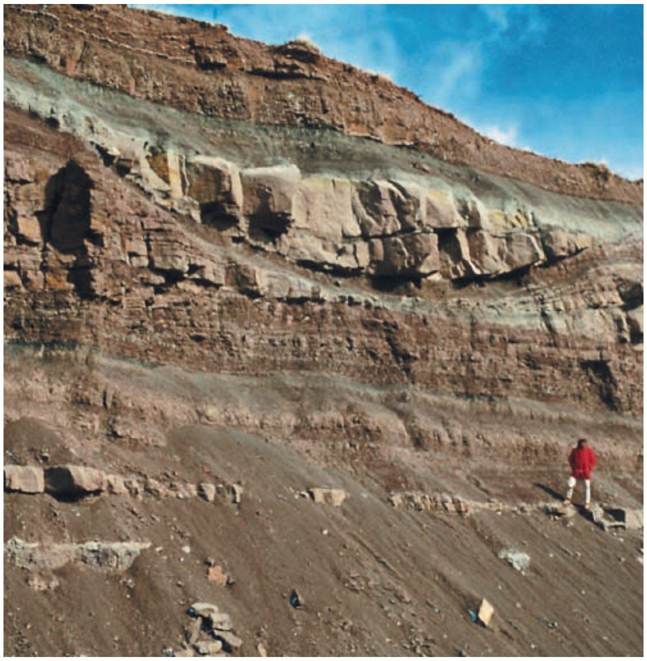
What are the major steps in the formation of sedimentary rock?

Each depositional system imprints specific characteristics on the rocks formed within it. A small depositional area within a system creates a **facies**—a body of rock with distinct chemical, physical, and biological characteristics created by the environment. Thus, a delta system produces many different facies, for example, sediment deposited in channels, between channels, and at the mouths of channels. Distinctive textures, compositions, sedimentary structures, and fossil assemblages develop in each facies. Illustrations of modern sedimentary systems, together with examples of the rocks they produce, are shown in Figures 5.14 through 5.25. Carefully study each of these photographs and the discussions in the captions.

Compaction and Cementation

The final stage in the formation of sedimentary rocks is the transformation of loose, unconsolidated sediment into solid rock. **Compaction** occurs when the weight of overlying material, which continually accumulates in a sedimentary environment, compresses the sediment buried beneath into a tight, coherent mass. Wet mud consists of 60 to 80% water, most of which is driven out during compaction. **Cementation** occurs when dissolved ions, carried by water seeping through pores, is precipitated. Common cementing minerals are calcite, quartz,

(A) Point-bar deposits in a modern river. *(Photograph by J. K. Rigby)*



(B) Ancient stream channel marked by sandstone lens interlayered with fine-grained clay and siltstone.

FIGURE 5.14 **Fluvial systems.** The great rivers of the world are the major channels by which erosional debris is transported from the continents to the oceans. Before reaching the ocean, most rivers meander across flat alluvial plains and deposit a considerable amount of sediment. Within this environment, sediment is deposited in stream channels, on bars, and on floodplains. Perhaps the most significant type of sedimentation occurs on bars on the insides of meander bends. Stream deposits have channels of relatively coarse sand or gravel cut into horizontal layers of fine silt and mud that were deposited on the flood plain.

(A) Modern alluvial fans in Death Valley, California.

(B) Ancient alluvial-fan deposits in central Utah.

FIGURE 5.15 **The alluvial-fan systems.** In many arid regions of the world, thick deposits of sedimentary rock accumulate in alluvial fans at the bases of mountain ranges. Deposition occurs here because stream channels widen and the slope decreases, causing the water to slow down and drop its sediment. Flash floods and debris flows are an important factor in this environment. Torrents from cloudbursts pick up the loose debris on the slopes of the mountain ranges and deposit it on the basin floor. The sediment in an alluvial fan characteristically is coarse-grained, and conglomerate is the most abundant rock type. In the central part of the basin, fine silt and mud can accumulate in temporary lakes and commonly are associated with the coarser fan deposits.

(A) Modern sand dunes in the Little Sahara Desert, Utah.

(B) Ancient dune deposits in Zion National Park, Utah.

FIGURE 5.16 **The eolian (wind) systems.** Wind is a very effective sorting agent. Small silt and dust grains are lifted high in the air and may be transported thousands of kilometers before being deposited where wind velocity drops. Sand is transported close to the surface and eventually accumulates in dunes. Gravel cannot be moved effectively by wind. In arid regions, a major process is the migration of sand dunes. Sand is blown up and over the dunes and accumulates on the steep dune faces. Large-scale cross-strata that dip in a downwind direction are thus formed. Ancient dune deposits have large-scale cross-strata consisting of well-sorted, well-rounded sand grains. The most significant ancient wind deposits are sandstones that accumulated in large dune fields comparable to the present Sahara and Arabian deserts and the great deserts of Australia. These sandstones are vast deposits of clean sand that preserve the large-scale cross-beds developed by migrating dunes.

(A) The margins of a valley glacier in eastern Canada. *(Photograph by J. D. Ives)*

(B) Ancient glacial sediments in central Utah.

FIGURE 5.17 **Glacial systems.** A glacier transports large boulders, gravel, sand, and silt suspended together in the ice. This material is eventually deposited near the margins of the glacier as the ice melts. The resulting sediment is unsorted and unstratified, with angular individual particles that rest on the polished and striated floor of the underlying rock. Fine-grained particles dominate in many glacial deposits, but angular boulders and pebbles are invariably present. Streams from the meltwaters of glaciers rework the unsorted glacial debris and redeposit it beyond the glaciers as stratified, sorted stream deposits. The unsorted glacial deposits are thus directly associated with well-sorted stream deposits from the meltwaters.

(A) The delta of the Nile River, Egypt, forms where the river empties into the Mediterranean Sea. *(Courtesy of NASA)*

(B) Ancient deltaic deposits in Tertiary rocks of the Colorado Plateau.

FIGURE 5.18 **Delta systems.** One of the most significant depositional systems occurs where major rivers enter the oceans and deposit most of their sediment in marine deltas. A delta can be very large, covering areas of more than 36,000 km^2. Commonly, deltas are very complex and involve various distinct subenvironments, such as beaches, bars, lagoons, swamps, stream channels, and lakes. Because deltas are large features and include both marine and nonmarine subenvironments, a great variety of sediment types accumulate in them. Sand, silt, and mud dominate. A deltaic deposit can be recognized only after considerable study of the sizes and shapes of the various rock bodies and their relationships to each other. Both marine and nonmarine fossils can be preserved in a delta.

(A) A modern beach on Cape Hatteras along the Atlantic Coast of the United States. *(Photograph © Tom Till)*

(B) Ancient beach deposits in central Utah form resistand sandstone beds alternating with shale (slopes).

FIGURE 5.19 **Shoreline systems.** Much sediment accumulates in the zone where the land meets the ocean. Within this zone, a variety of subenvironments occurs, including beaches, bars, spits, lagoons, and tidal flats. Each has its own characteristic sediment. Where wave action is strong, mud is winnowed out, and only sand or gravel accumulates as beaches or bars. Beach gravels accumulate along shorelines, where high wave energy is expended. The gravels are well sorted and well rounded and commonly are stratified in low, dipping cross-strata. Ancient gravel beaches are relatively thin. They are widespread and commonly are associated with clean, well-sorted sand deposited offshore.

(A) A lagoon along the central Atlantic coast of the United States. *(Courtesy of NASA)*

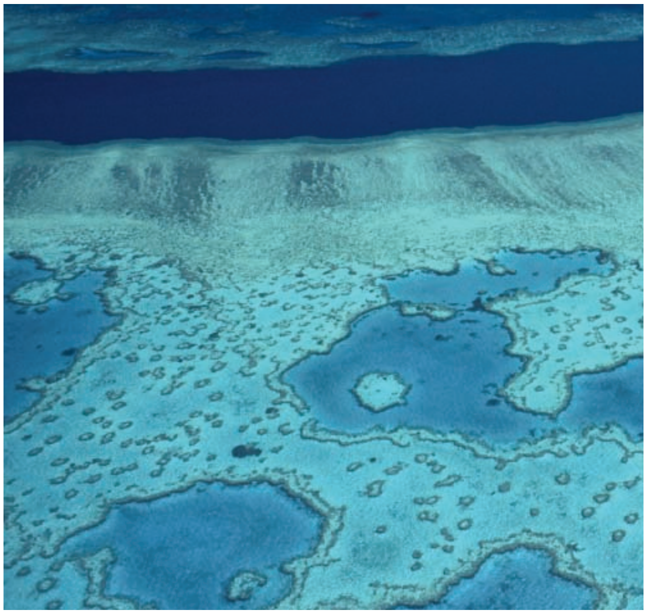
(B) Ancient lagoonal deposits with thick beds of coal in sandstone in eastern Wyoming.

FIGURE 5.20 **Lagoon systems.** Offshore bars and reefs commonly seal off part of the coast, forming lagoons. A lagoon is protected from the high energy of waves, so the water is relatively calm and quiet. Fine-grained sediment, rich in organic matter, accumulates as black mud. Eventually, the lagoon may fill with sediment and evolve into a swamp. Where the bottom vegetation provides enough organic matter, a coal deposit may form. The rise and fall of sea level shift the position of the barrier bar, and thus the organic-rich mud or coal formed in the lagoon or swamp is interbedded with sand deposited on the barrier island.

(A) A modern tidal flat in the Maritime Provinces of Canada. *(Courtesy of Candaian Department of Energ, Mines, and Resources)*

(B) Ancient tidal flat deposits in southern Utah.

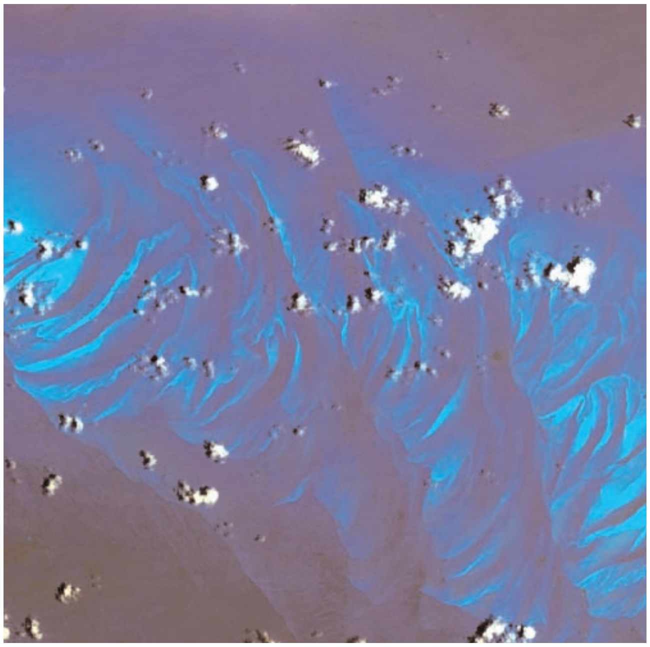
FIGURE 5.21 **Tidal-flat systems.** The tidal-flat environment is unique in being alternately covered with a sheet of shallow water and exposed to the air. Tidal currents are not strong. They generally transport only fine silt and sand and typically develop ripple marks over a broad area of the tidal flat. Mud cracks commonly form during low tide and are subsequently covered and preserved. Ancient tidal-flat deposits are thus characterized by accumulations of silt and mud in horizontal layers with an abundance of ripple marks and mud cracks. In restricted settings, evaporites can form on tidal flats.



(A) Australia's Great Barrier Reef is a coral reef on the eastern shore. *(Jan Arthus/CORBIS.)*

(B) An ancient reef from the Paleozoic Era in the Guadalupe Mountains of west Texas *(William A. Bake/CORBIS)*

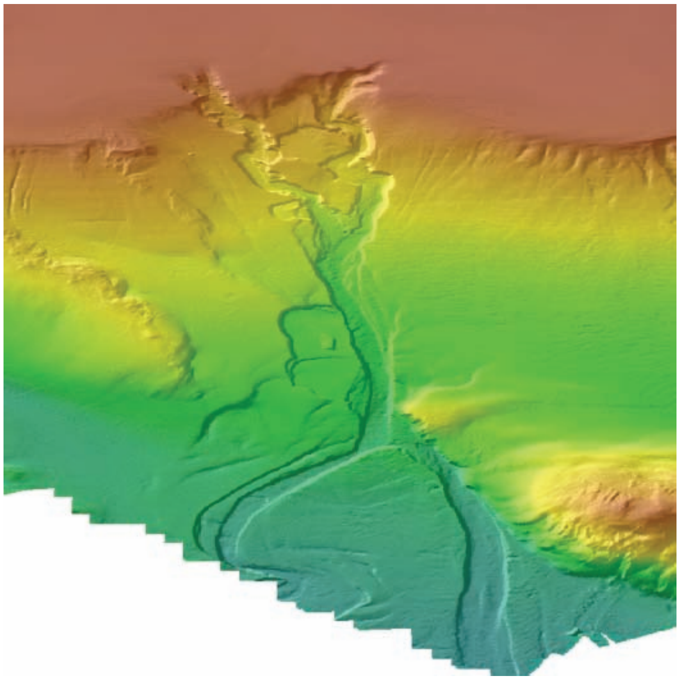
FIGURE 5.22 **Organic-reef systems.** An organic reef is a solid structure of calcium carbonate constructed of shells and secretions of marine organisms. The framework of most reefs consists of a mass of colonial corals and forms a wall that slopes steeply seaward. Wave action continually breaks up part of the seaward face, and blocks and fragments of the reef accumulate as debris on the seaward slope. A lagoon forms behind the reef, toward the shore or toward the interior of the atoll (organic reef), and lime, mud, and evaporite salts may be deposited there. Gradual subsidence of the seafloor permits continuous upward growth of reef material to a thickness of as much as 1000 m. Because of their limited ecological tolerance (corals require warm, shallow water), fossil reefs are excellent indicators of ancient environments.



(A) A modern shallow-marine environment in the Bahamas as seen from space. The light ridges are drifts of carbonate sediment. *(Courtesy of U.S. Geological Survey and EROS Data Center.)*

(B) Ancient shallow-marine sediments in eastern Nevada are made of many layers of limestone.

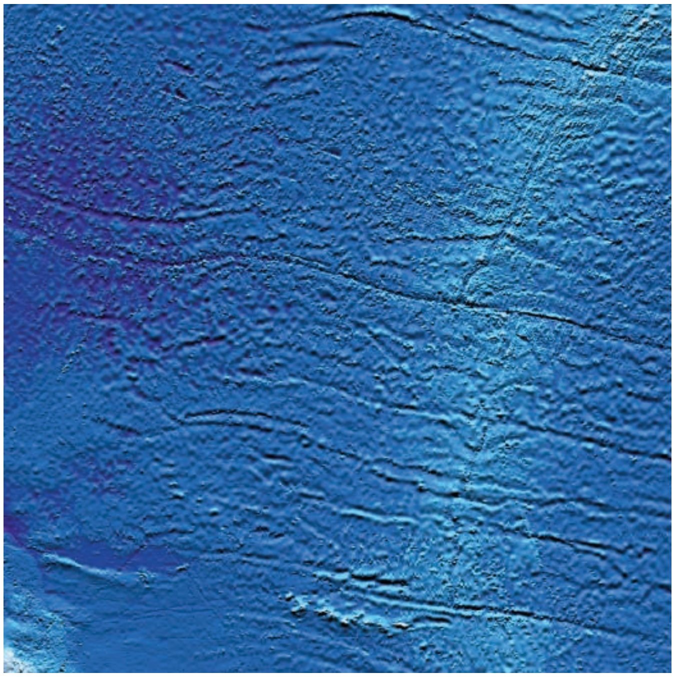
FIGURE 5.23 **Shallow-marine systems.** Shallow seas border most of the world's land area and can extend to the interior of a continent, as do Hudson Bay, the Baltic Sea, and the Gulf of Carpentaria (in northern Australia). The characteristics of the sediment deposited in the shallow-sea environment depend on the supply of sediment from the land and the local conditions of climate, wave energy, water circulation, and temperature. If there is a large supply of land-derived sediment, sand and mud accumulate. If sediment from the land is not abundant, limestone is deposited. Ancient shallow-marine deposits have thin, widespread, interbedded layers of sandstone, shale, and limestone.



(A) Submarine fan with its distributary channels sits at the base of the continental slope offshore California. *(Courtesy of Michelle Hurst; data from U.S. Geological Survey)*

(B) Ancient series of folded turbidites in southern France.

FIGURE 5.24 **Continental slope-systems.** Sediment on the continental slope is dominated by turbidites. The deposits are typically a series of graded beds, with each layer extending over a large area. Such beds are easily distinguishable from sediment deposited in most other environments. The turbidites accumulate to form a cone of debris at the foot of the continental slope called a submarine fan; most are at the mouths of submarine canyons. Channels filled with porous sandstone weave complicated patterns through the fan, as shown on this shaded relief map of a submarine fan off the coast of southern California. These sandstones that fill the channels are important hosts for oil in deep-marine environments.



(A) Thin layers of deep marine sediment form on abyssal plains on the flanks of the midocean ridge (right). *(Courtesy of Chalk Butte, Inc.)*

(B) Thin beds of ancient deep marine cherts now exposed in coastal California. Such cherts are interbedded with fine mudstones.

FIGURE 5.25 **Deep-marine systems.** Deep-marine sediment accumulates on the floor of the open ocean, far from continents. This material consists of shells of microscopic organisms and fine particles of mud that are carried in suspension and gradually sink. Biochemical chert in thin beds is a common deep-marine sediment. However, the most abundant sediment is a fine-grained brown or red clay. Silt blown in by the wind is another important sediment in the deep ocean basins. Calcium carbonate does not accumulate in the deepest oceans, but may be deposited on midocean ridges where the water is shallower. In this environment, sediment accumulation rates are very low and the beds are typically thin.

and iron oxides. This postdepositional crystallization of cement holds the grains of sediment together and is a fundamental process in transforming sediment into solid rock.

STRATIGRAPHIC SEQUENCES

Layers of sedimentary rocks can be grouped into formations, and formations can be grouped into sequences that are bounded by erosion surfaces. These formations and sequences form an important interpretive element in the rock record.

There are more than 17,000 formally recognized and named formations in the United States, each covering an area of up to 300,000 km^2. Each formation is a group of beds of a distinctive rock type that formed at a specific time and place. They are, thus, the fundamental rock units studied by geologists. On a regional scale, these formations are like a deck of cards scattered across a table with most cards overlapping another. In many areas, the total succession of sedimentary formations is thousands of meters thick. Stratification occurs on many scales, so there are typically many separate beds within a formation and innumerable thin laminae within the layers of each bed.

On a larger scale, formations and their stratification are produced by changes in the depositional system; each change causes a different type of sediment to form. One of the simpler and more common patterns in a vertical succession is the cycle of sandstone-shale-limestone-shale-sandstone (Figure 5.26). This pattern is produced by advance (**transgression**) and retreat (**regression**) of a shallow sea across a continental margin. The base of the sedimentary layers is a preexisting surface produced by erosion—an **unconformity.** In Figure 5.26A, sand is accumulating on the floodplain of a river system and along the shore, fine-grained mud is carried farther and is accumulating just offshore, and calcium carbonate precipitates from solution beyond the mud zone. All three types of sediment are deposited simultaneously, each in a different environment.

As relative sea level rises, each environment shifts landward (Figure 5.26B, C). Beach sands are deposited over stream sediments, offshore mud is deposited over the previous beaches, and carbonate is deposited over the mud. As transgression continues, the layers of sand, mud, and carbonate are deposited farther and farther inland.

Why do geologists study sedimentary sequences and not just the individual layers?

If relative sea level drops (Figure 5.26D), mud is deposited over limestone and near-shore sand over mud. The net result is a long wedge, or layer, of limestone encased in a wedge of shale, which in turn is encased in a wedge of sandstone. This package of sediment is bounded below and above by an unconformity. Subsequent uplift and erosion of the area reveal a definite **sequence** of rock (Figure 5.26E). Beginning at the basal unconformity, sandstone is overlain by shale and limestone, which in turn are overlain by shale and sandstone.

Sequence Stratigraphy

Traditionally, rock formations have been identified and classified on the basis of rock type—such as the limestones and sandstone bodies that form the prominent cliffs in the photograph in Figure 5.1—but they can also be grouped into larger sequences of strata separated by major unconformities. The study of such sequences of rock is known as *sequence stratigraphy* and is an attempt to detect worldwide changes in sea level and to document tectonic movements that affect sea level in smaller regions. Sequences of rock bounded by unconformities reflect important events in Earth's history that have regional or even worldwide

(A) The sea begins to expand over an erosional unconformity. The original shoreline is marked by sand deposits that grade seaward into mud and lime (carbonate sediment).

(B) The sea transgresses farther inland, depositing a sheet of sand overlain by mud (gray) and lime (tan).

(C) With continued transgression of the sea, mud is deposited on top of the sand at the position of the original shoreline.

(D) A regression of the sea deposits shoreline sand over the offshore mud. Thus, the vertical succession of sediment at the position of the original shoreline is sand, mud, carbonate, mud, and sand. The package of sequence is bounded above and below by an unconformity.

(E) Much later the eroded exposure of a transgressive-regressive sequence shows the cycle from bottom to top: sandstone, shale, limestone, shale, and sandstone.

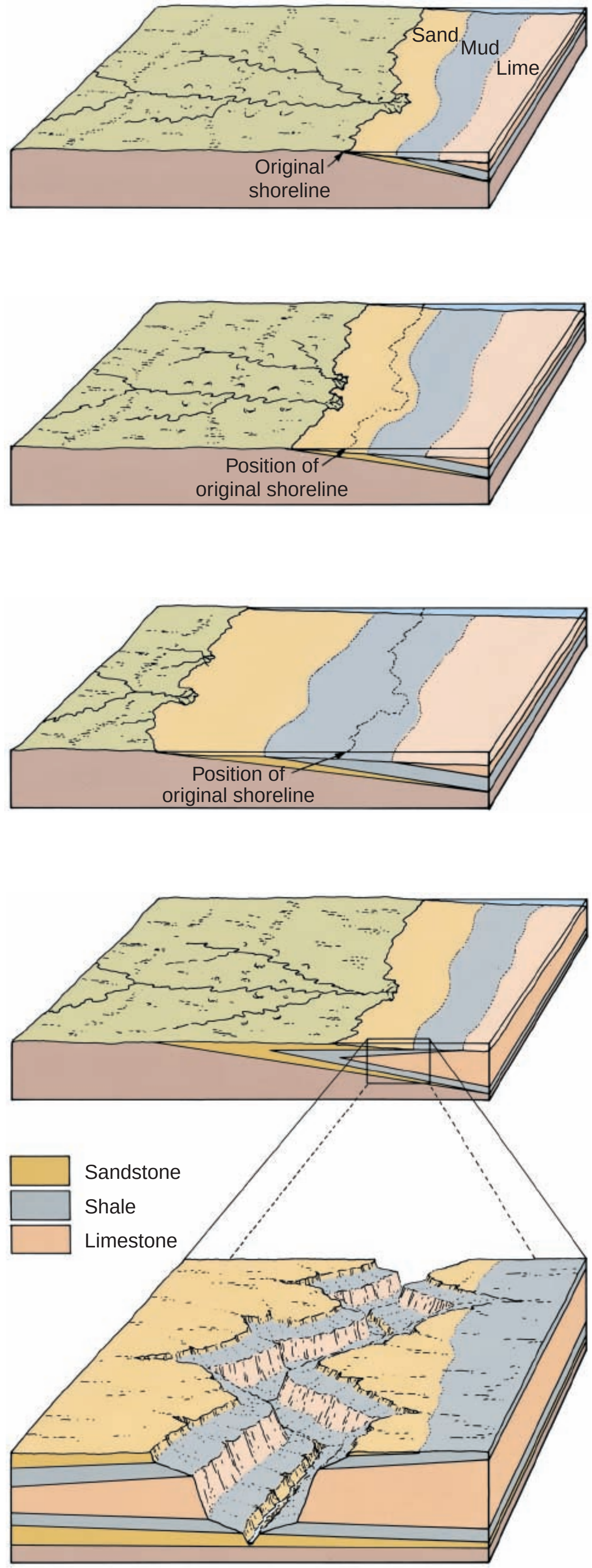


FIGURE 5.26 **A sequence of sediments deposited by transgression and regression of a shallow sea** is represented in these schematic diagrams. Sand accumulates along the beach, mud is deposited offshore, and calcite is precipitated farther offshore, beyond the mud. As the sea expands over the continent, these shallow-marine environments move inland, producing a vertical sequence of sand, mud, and carbonate sediment. When the sea recedes off the continent, mud is deposited over the carbonate sediment, and sand is deposited over the mud. The net result is a vertical sequence of sedimentary layers: sandstone, shale, limestone, shale, and sandstone.

significance. Over much of the last 600 million years, the seas repeatedly transgressed and regressed across the continental shelves and over the platforms, leaving a record of shallow-marine deposits separated by erosional surfaces.

These sequences bounded by unconformities are created by major changes in the position of the shoreline. Such relative sea level changes can be caused by variations in the total amount of water in the oceans or by tectonic events. For example, the amount of water in the oceans drops during periods of glaciation when water is stored on continents. During periods of rapid seafloor spreading, ocean ridges become inflated; this reduces the volume of ocean basins, and forces water to spill over continental lowlands. Changes in ocean basin volume also occur when continents collide.

The concepts of sequence stratigraphy are extensively used by geophysicists interpreting seismic records of rocks in the subsurface. The principal erosional surfaces marking transgressions and regressions have been identified from seismic logs from all over the world. Consequently, a clear picture of changing sea level through time is emerging (Figure 5.27).

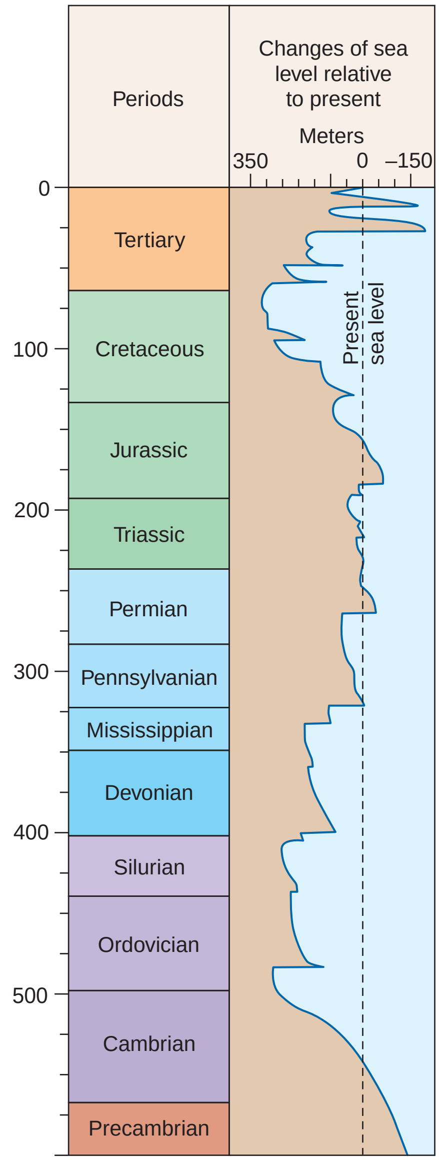


FIGURE 5.27 Sequence stratigraphy identifies the global changes of relative sea level. The major transgression-regression cycles are probably produced by large tectonic events that change the volume of the ocean basins. Shorter cycles of transgression and regression are superimposed on these major changes and probably are caused by glaciation and regional tectonic events.

SEDIMENTARY SYSTEMS AND PLATE TECTONICS

> Plate tectonics has a profound influence on the origin of sedimentary rocks in that it controls sediment sources, pathways, climate zones, and depositional systems. As a result, each major tectonic setting produces a distinctive sequence of sedimentary rocks.

Although the nature of sedimentary rocks depends on many factors (depth and velocity of water, ocean currents, biology, and sediment source area, for example), plate tectonics plays a major role in global aspects of sediment deposition and the sequences of rock that are produced. Tectonics controls the extent of shallow seas upon the stable platform, the distribution of continental margins, the development of sedimentary basins, and the origin of mountain belts that are the sources of many sediments. Plate movement also controls rates of crustal uplift and subsidence, and therefore the rates of erosion and deposition. In addition, plate tectonics also has a prime control on the courses of rivers (which determine where the bulk of clastic sediment is deposited), and the topography and structure of continents in general. Let us consider some of the tectonic settings in which major bodies of sedimentary rocks form (Figure 5.28).

On the continents, sediment forms by weathering and is then transported across the stable platform from distant highlands and locally accumulates to form thin deposits that include stream sands and shallow-marine mudstones and limestones. Broad basins may form on the stable platform in which thicker sequences of sediment accumulate. However, most sediment carried all the way to the sea is deposited as shallow-marine sediment on the continental margin.

Continental rift valleys at incipient divergent plate boundaries receive a distinctive suite of conglomerate, sandstone, lake deposits, and evaporites (if the climate is arid). As the rift evolves into an open seaway, the continental margin subsides as it cools; shallow seas spread over the margin and across part of the stable platform to form a broad continental shelf. A thick wedge-shaped deposit of sediment forms as the margin continues to subside.

Farther from shore, on the continental slope, turbidity currents move sediment toward the abyssal plains to form deep-sea fans comprised of turbidites. Even farther from the continent, deep-ocean basins accumulate organic ooze (dominated by siliceous diatoms) and wind-blown dust. Carbonate sediments form in shallower parts of the oceans. These sediments slowly settle out of seawater to form thin layers of brown mud on the igneous part of the oceanic crust.

STATE OF THE ART

Ocean Drilling Program: Probing the Deep Blue Sea

One of the most ambitious scientific endeavors in the study of Earth is the effort to collect samples from below the floor of the deep oceans by drilling through its outer layers. The program employs specially designed research ships that carry huge drills and long strings of pipe. Imagine the difficulty in lowering a slender drilling stem 8000 m long to the floor of the ocean, then drilling another 2000 m or more through layers of siliceous organic ooze and then drilling into solid igneous rock. Once drilled, core segments about 10 m long and 10 cm in diameter are slowly pulled to the deck of the ship, where they are cut in two in preparation for detailed laboratory studies.

Ocean cruises of this sort require many crew members and scientific staff and extend over several months. The research is expensive and only a few nations have mounted this type of research. Since 1985, the United States has coordinated an international program called the Ocean Drilling Program. Scientists from the United Kingdom, Japan, Germany, Australia, New Zealand, and other nations also participate. *JOIDES Resolution* has drilled in the Atlantic, Pacific, Indian, and Arctic oceans. In the first 15 years of the program, more than 180,000 m of core have been recovered from nearly 1500 holes drilled in 80 different locations. Its predecessor, the Deep Sea Drilling Program, probed the seafloor for nearly 20 years.

In addition to the huge drill, scientists on board have at their disposal a complete array of analytical instruments in the ship's twelve laboratories. They examine samples of sediment under microscopes to see what fossils they contain, X ray cores of sedimentary and igneous rocks to determine their composition, and probe the cores with magnetometers and thermometers and other instruments. After the cruise, these rocks and sediment are stored in a core library and become invaluable resources for scientists around the world.

The empty drill holes are often turned into "laboratories" themselves. Instruments are lowered into the holes to record the temperature, measure heat flow, take water samples, and generally record the physical and chemical properties of the oceanic crust.

Why spend months at sea and go to such great expense? The scientific payoff for such deep-sea drilling programs has been tremendous. Most of what we know about past climate change has come from painstaking studies of the sediment samples recovered by deep-sea drilling, including the timing of past glacial epochs and unravelling the Milankovitch cycles (p. 401). Ocean drilling has revealed evidence for the meteorite impact that marked the end of the Mesozoic Era (p. 732). Other drilling opportunities have focused on understanding the origin of massive oceanic plateaus that some geologists think are produced by rapid submarine eruptions of flood lavas (p. 618). Some projects drilled through the entire sedimentary cover to reveal exactly what types of igneous rocks are below the oceanic sediment and to allow for heat flow measurements (p. 44) that tell us the thickness of the lithosphere. These cores help us unravel Earth's past and present and conjecture about its future. In essence, these seafloor cores are cylindrical slices of Earth's history.

(Photographs courtesy of the Ocean Drilling Program, Texas A&M University)

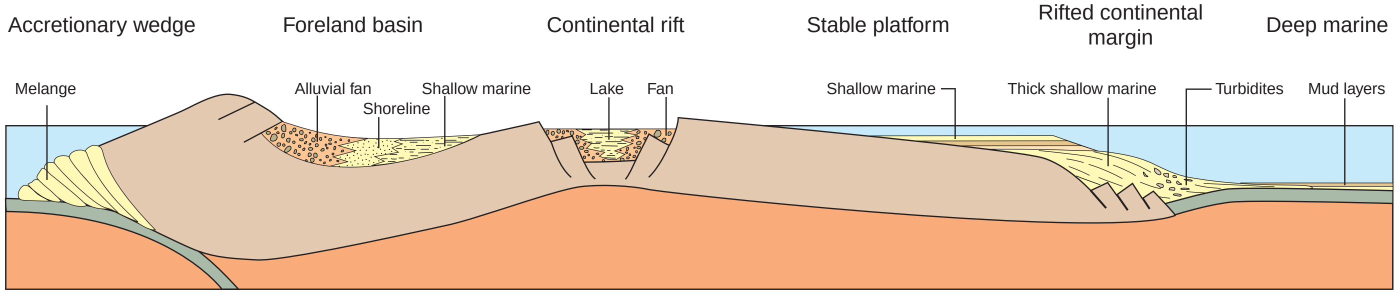


FIGURE 5.28 **Plate tectonics** exerts fundamental controls on sedimentary systems. The most important types of sedimentary basins form at convergent margins, divergent margins that evolve into passive continental margins, and shallow basins that form on the stable platform. Deep-ocean basins also have distinctive sediments.

How does plate tectonics influence the nature of sedimentary rocks?

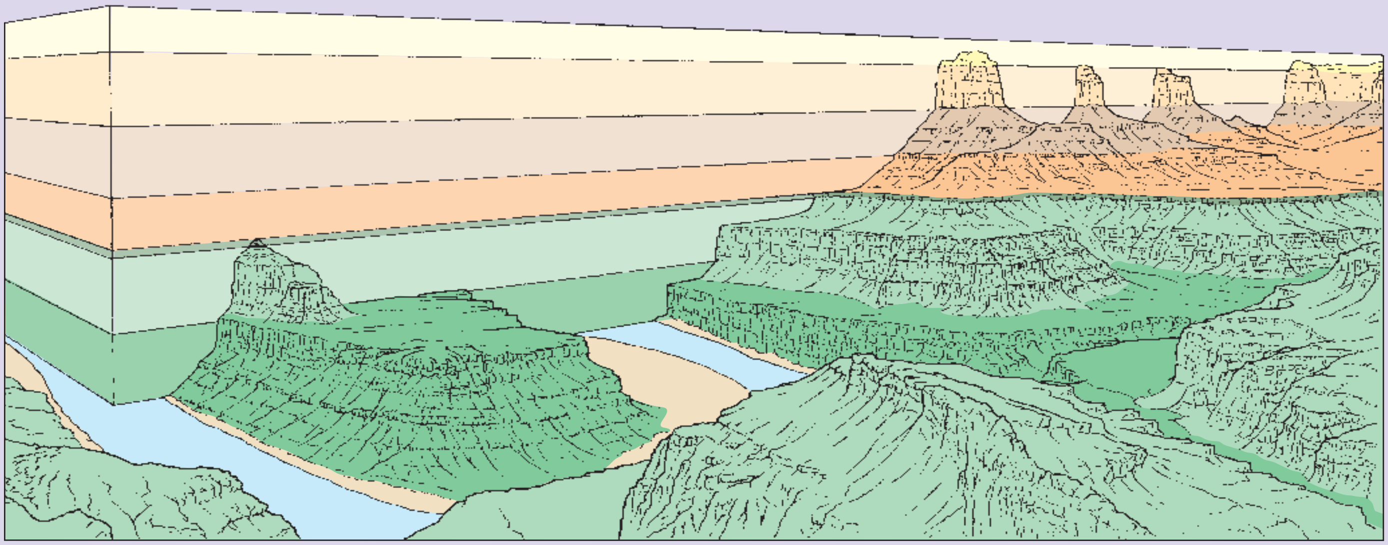
At convergent plate boundaries, a folded mountain belt typically has a subsiding basin on its landward side. Erosional debris from the mountains accumulates rapidly in alluvial fans containing conglomerates and associated sandstones and shales. Subsidence in this basin may be so great that the region may be inundated by a shallow sea. On the ocean side of the mountain belt, the distance to the sea is short and there is no broad continental shelf. Large deltas seldom form on subducting continental margins because drainage basins are small. Instead, sediment transported from the mountain toward the boundary accumulates in the adjacent deep-sea trench where turbidites are common. Some of the sediment is consumed with the descending plate. However, much continental sediment is scraped off, and together with deep-marine mud and basalt on the descending plate, is plastered against the continent. These mixed deposits are known as *mélange.*

Thus, we see that each of the various tectonic settings—continental rift valleys, rifted and subsiding continental margins, deep-ocean floor, and convergent plate boundaries—produce distinctive basins that fill with unique kinds of sedimentary rock.

An indirect, but also profound, control tectonics has on sedimentation is the drifting of continents into different climate zones (see Figure 9.21). This affects weathering, including the rate and nature of the sediment produced. For example, in the tropics, lush vegetation may form coal swamps. If the continent moves into the low-latitude deserts, wind-blown sand is deposited on the coal. If the continent continues northward, glacial sediments might eventually be deposited upon the desert sand. In short, plate tectonics influences not only the different types of sedimentary basins where sediment accumulates, but also the basic stratigraphic patterns in a sequence of sedimentary rock.

From a scientific point of view, sedimentary rocks are important for the geologic history they preserve. A record of the past is written in the layers of sedimentary rock. From this record, we can interpret such things as the origin and destruction of old mountain systems, the erosion of continents, climate changes, and even the evolution of life.

GeoLogic Sedimentary Rocks at Dead Horse Point



The spectacular scenery of Utah's Dead Horse Point is due to the colorful succession of horizontal sedimentary formations that were carved by stream erosion into vertical cliffs and slopes. To most people the visual impact of this scenery is enough and they are satisfied. But there is much more to this scene than you might think. The rocks and landforms are documents of history which, if understood, is more fascinating than the scenery.

Observations

1. The landscape was formed by stream erosion of these nearly horizontal sedimentary rock layers.
2. The rock units were once much more extensive than what we see here. Some formations once covered an area of more than 250,000 km^2.
3. Each major rock layer, or formation, was formed by a specific sedimentary process. Some formed by deposition by river systems, others by deposition on tidal flats, and others by deposition in deserts.

Interpretations

The geologic interpretation of this scene begins by trying to visualize the original extent of the rock sequences as they existed before erosion. The layers of rock also extended far beyond the area shown in the photograph, one superimposed upon another. Details of the sedimentary environments in which each rock unit was deposited come from studying the composition, texture, and structure of each major layer. Subsequent to deposition, compaction and cementation, the rock layers were uplifted and the cliffs were formed by erosion of the hard resistant sandstone, whereas the slopes were carved on soft nonresistant shale.

KEY TERMS

alluvial fan (p. 130)
barrier island (p. 130)
beach (p. 130)
bed (p. 125)
bedding plane (p. 117)
biochemical rocks (p. 122)
cementation (p. 130)
chalk (p. 122)
chemical precipitate (p. 122)
chert (p. 123)
clastic (p. 118)
claystone (p. 120)
compaction (p. 130)
conglomerate (p. 119)
cross-bedding (p. 126)
deep-ocean basin (p. 130)
delta (p. 130)
dolostone (p. 123)
dune (p. 126)
eolian (p. 132)
evaporite (p. 124)
facies (p. 130)
fluvial (p. 130)
formation (p. 116)
fossil (p. 117)
glacier (p. 130)
graded bedding (p. 126)
gypsum (p. 124)
lagoon (p. 130)
lamina (p. 120)
limestone (p. 122)
mudrock (p. 120)
mud cracks (p. 127)
oolite (p. 122)
reef (p. 130)
regression (p. 137)
ripple marks (p. 127)
rock salt (p. 124)
sandstone (p. 119)
sand wave (p. 126)
sediment (p. 116)
sedimentary rock (p. 116)
sedimentary structure (p. 125)
sedimentary system (p. 129)
sequence (p. 137)
shale (p. 120)
shallow marine (p. 130)
siltstone (p. 120)
stratification (p. 125)
stratum (p. 116)
submarine fan (p. 130)
tidal flat (p. 130)
transgression (p. 137)
turbidite (p. 126)
turbidity current (p. 126)
unconformity (p. 137)
weathering (p. 129)

REVIEW QUESTIONS

1. List the characteristics that distinguish sedimentary rocks from igneous and metamorphic rocks.
2. What is the principal mineral in sandstone? Why does this mineral dominate?
3. What is the major difference between the various kinds of clastic sedimentary rocks?
4. What is the principal cause of grain-size variations in clastic sediment?
5. How do limestones differ from clastic rocks?
6. What is the mineral composition of limestone?
7. How do evaporites form? How are they different from clastic sedimentary rocks?
8. Show, by a series of sketches, the characteristics of stratification, cross-bedding, and graded bedding.
9. How could you recognize an ancient turbidity current deposit now exposed in a mountain?
10. What rock types form in the following sedimentary systems: (a) delta, (b) lagoon, (c) alluvial fan, (d) eolian, (e) organic reef, and (f) deep marine?
11. How does plate tectonics control the character of sedimentary rocks deposited on a continental margin that is far from a modern plate boundary?
12. How does a transgression followed by a regression of the sea produce the vertical sequence sandstone, shale, limestone, shale, sandstone?

ADDITIONAL READINGS

Adams, A. D., W. S. MacKenzie, and C. Guilford. 1984. *Atlas of Sedimentary Rocks Under the Microscope.* New York: Wiley.
Blatt, H., and R.J. Tracy. 1996. *Petrology: Igneous, Sedimentary, and Metamorphic*. New York: Freeman.
Boggs, S. 2001. *Principles of Sedimentology and Stratigraphy.* Upper Saddle River, NJ: Prentice Hall.
Carozzi, A. V. 1993. *Sedimentary Petrography.* Englewood Cliffs, N.J.: Prentice Hall.
Open University. 1998. *The Ocean Basins: Their Structure and Evolution.* Oxford: Butterworth and Heinemann.
Prothero, D.R., and F. Schwab. 1996. *Sedimentary Geology.* New York: Freeman.
Reading, H. G. 1996. *Sedimentary Environments: Processes, Facies, and Stratigraphy.* Oxford: Blackwell.
Tucker, M. E. 2001. *Sedimentary Petrology.* Oxford: Blackwell.

MULTIMEDIA TOOLS

Earth's Dynamic Systems Website
The Companion Website at **www.prenhall.com/hamblin** provides you with an on-line study guide and additional resources for each chapter, including:

- On-line Quizzes (Chapter Review, Visualizing Geology, Quick Review, Vocabulary Flash Cards) with instant feedback
- Quantitative Problems
- Critical Thinking Exercises
- Web Resources

Earth's Dynamic Systems CD
Examine the CD that came with your text. It is designed to help you visualize and thus understand the concepts in this chapter. It includes:

- Slide shows with more examples of sedimentary rocks and sedimentary environments
- Videos showing the formation of sedimentary structures
- A direct link to the Companion Website