

# Sediments and 6

## Sedimentary Rocks

### OUTLINE

- 6.1 Sediment
- 6.2 Types of Sedimentary Rock
- 6.3 Sedimentary Structures
- 6.4 Interpreting Sedimentary Rocks:  
Depositional Environments

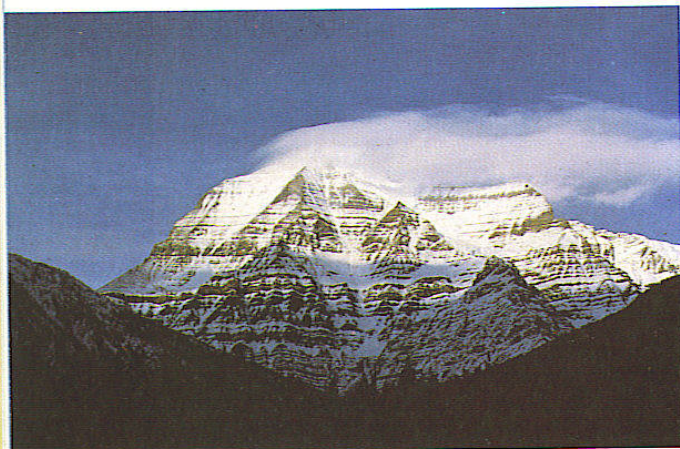
**S**edimentary rocks tell a story of destruction and rebuilding. They are part of the Earth's cycle of continuous change; they remind us that, over the great length of geologic time, even the solid rocks that make up the Earth's crust are transient features of the landscape. All rocks at the Earth's surface disintegrate slowly by chemical and physical weathering. The products of weathering are both solid particles, such as grains of sand, and ions dissolved in water. These weathering products erode and are carried away by running water, wind, glaciers, and gravity to lower elevations where they collect and may become cemented together to form new materials called **sedimentary rocks**.

Most of the material eroded from the Earth's surface accumulates in coastal areas where rivers enter the sea. Lesser amounts collect in lowlands, valleys, and basins on the land surface. However, sedimentary rocks are often found on the tops of mountains. The Catskills in New York, the Canadian Rockies in Alberta, and even the summit of Mount Everest, the highest peak in the world, are composed of sedimentary rocks. Their mere existence in the lofty places of the globe tells a story of uplift and dynamic activity in the crust.

Sedimentary rocks make up only about 5 percent of the total volume of the Earth's crust. However, because sedimentary rocks form on the Earth's surface, that relatively small volume is spread in a thin veneer over underlying igneous and metamorphic rocks. As a result, sedimentary rocks cover about 75 percent of the surfaces of continents.

Not only are sedimentary rocks important because they cover most of the land surface of our planet, but in addition, many types of sedimentary rocks have high economic value. Coal, a major energy resource, is a sedimentary rock. Limestone is an important building material, both as a stone and as the primary ingredient in cement. Ores of





Mount Robson, a limestone mountain in British Columbia.

copper, lead, zinc, iron, gold, and silver concentrate in certain types of sedimentary rocks. Oil and gas form and concentrate in sedimentary rocks.

There are four stages in the formation of sedimentary rocks. First, sediment forms by weathering of existing rocks. The sediment is then eroded and transported from its point of origin by water, wind, glaciers, and gravity. Eventually, the transported sediment is deposited. Most deposition occurs in the ocean along the margins of continents, although inland valleys and lakes can also be depositional sites. Finally, as layers of sediment accumulate and are buried by younger layers, the loose sediment gradually converts to hard rock by one or more of a group of processes called **lithification**. Thus, sedimentary rocks form when sediment is lithified. Each of these steps is discussed in turn.

## 6.1 Sediment

### Formation of Sediment

**Sediment** refers collectively to all solid particles transported and deposited by water, wind, glaciers, and gravity. It also includes solids chemically precipitated from solution or precipitated by organisms. Sediment forms loose, unconsolidated layers at the Earth's surface.

There are many different kinds of sediment. Most types are familiar. The sand on a beach, pebbles and cobbles in a river bed, dust in the air, mud in a puddle, and boulders suspended in glacial ice are all sediments. Accumulations of shell fragments near

a reef in the ocean, and salt deposited on the shores of Great Salt Lake in Utah are also sediments.

Sediment forms when rocks weather. **Clastic sediment** is composed of fragments of weathered rock. Although most clastic sediment consists of fragments of weathered silicate rocks and minerals, **bioclastic sediment** is composed of the broken remains of organisms, such as shell fragments.

Clastic sediment and many clastic sedimentary rocks are classified and named according to particle size (Table 6-1). **Gravel** includes all rounded particles with a diameter greater than 2 millimeters. Angular particles in the same size range are called **rubble**. Gravel is further subdivided on the basis of size into **pebbles**, **cobbles**, and **boulders**. **Sand** grains range between  $\frac{1}{16}$  and 2 millimeters in diameter. Individual grains of sand can be felt when a sandy sediment is rubbed between the fingers, and they can be seen with the naked eye. Sedimentary grains in the size range from  $\frac{1}{256}$  to  $\frac{1}{16}$  millimeter are **silt**. Individual silt grains cannot be resolved with the naked eye, and they feel smooth when rubbed between the fingers but gritty when rubbed between your teeth. **Clay** is all material less than  $\frac{1}{256}$  millimeter in diameter. Clay is so fine that it feels smooth even when rubbed between your teeth. Geologists often rub a small amount of sediment or rock between their front teeth to distinguish between silt and clay. (Don't use this test for sediments found in polluted streams.) **Mud** is wet silt and clay.

Chemical weathering dissolves ions in water. Strictly speaking, dissolved ions are not "sediment" because they are not particles, although they are transported and deposited as part of the overall sedimentary process. In certain environments dissolved ions may precipitate directly to form **chemical sediment**. Large sedimentary deposits of halite (table salt) and some limestone form in this way.

Table 6-1. Sizes and Names of Sedimentary Particles and Clastic Rocks

Diameter (mm)	Sediment		Clastic Sedimentary Rock
256 —	Boulders	Gravel (rubble)	Conglomerate (rounded particles) or breccia (angular particles)
64 —	Cobbles		
2 —	Pebbles		
$\frac{1}{16}$ —	Sand		Sandstone
$\frac{1}{256}$ —	Silt	Mud	Siltstone
	Clay		Claystone or shale
			Mudstone



## Erosion and Transport of Sediment

After sediment forms by weathering, it erodes and is transported by moving water, wind, glaciers, and gravity. Of the four, streams and rivers carry the greatest amount of sediment. Since nearly all streams eventually empty into the oceans, most sediment is transported to coastlines.

Sediment transport is fundamentally a gravity-driven process (Fig. 6-1). Since running water flows downhill, all sediment and dissolved ions carried by water also move toward lower elevations. Glaciers and their sediments also flow downhill. Windblown sand and silt may be carried uphill for short distances, but the ultimate path of these sediments, too, is downhill in response to the pull of gravity.

Clastic sedimentary particles are modified as they are carried from sites where they form to sites where they are deposited. The angular rubble shown in Figure 6-2A was formed by mechanical weathering near the summit of Trapper Peak, the highest mountain in the Bitterroot Range of western Montana. The rounded cobbles shown in Figure 6-2B lie in the stream bed of the West Fork of the Bitterroot River at the base of Trapper Peak. They originally formed as angular rubble on the peak. This conversion of sharp-edged rocks to rounded ones, called **rounding**, occurred during transport of only a few kilometers. Rounding is characteristic of transport by water and wind. However, it is obvious that water and wind are too soft to wear away rock. Rounding is caused when rock particles tumble against each other as they are transported. Particles ranging in size from coarse silt to boulders become

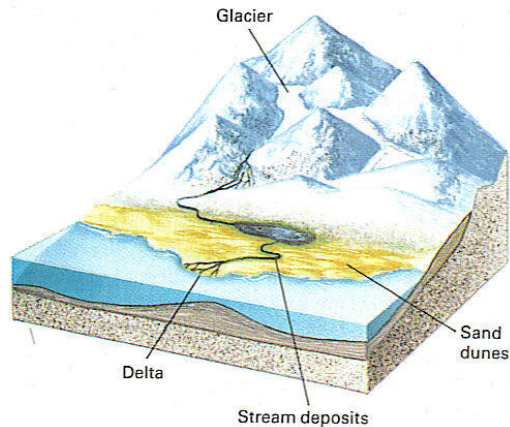
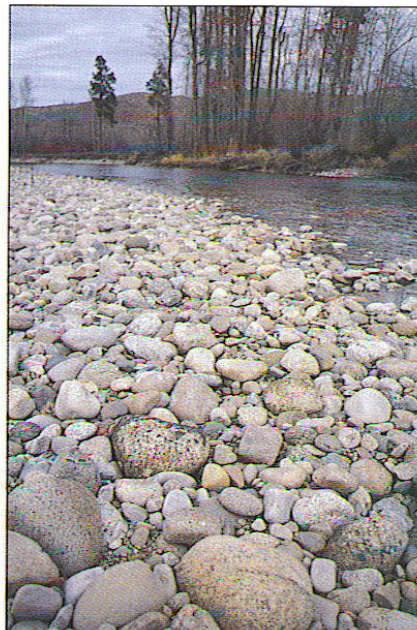


Figure 6-1 Sediment and dissolved ions are transported downhill by water and glaciers. They may be deposited temporarily in many different environments along the way, but eventually most sediment reaches the ocean.

rounded during transport. Finer particles do not round as effectively because they are so small and light that water and even wind, to some extent, cushion them as they bounce along, minimizing abrasion. Particles carried by ice are not rounded during transport for the same reason. The ice between the particles prevents them from abrading each other. The rounded gravel so common in sediment deposited by glaciers was abraded by stream transport before or after it was incorporated into a glacier.

Figure 6-2 (A) Angular rubble formed by mechanical weathering near the summit of Trapper Peak, Bitterroot Mountains, western Montana. (B) Rounded boulders in the West Fork of the Bitterroot River just below Trapper Peak.





Flowing water and wind also separate sediments according to particle size, a process called **sorting**. Figure 6-3 shows a profile of a stream flowing from the mountains out onto the plains. Near its source, the stream bed is steep. During periods of high flow, especially during floods, the flow is rapid. Faster flows have higher energy and can transport larger, heavier particles. Therefore, large boulders are transported in the steep upper portion of a stream. As the steepness of a stream decreases, its energy diminishes. The large boulders are deposited but the smaller particles are carried on downstream. Since the steepness of a stream typically decreases in the downstream direction, the largest sediments are usually found near the headwaters and the sediments become progressively finer downstream.

If you live or travel in a mountainous area, you can see good examples of sediment rounding and sorting by streams for yourself. If you begin driving downstream from the mountains, you will notice that along any stretch of stream most of the particles are rounded and of the same size and that the average size of the particles decreases as you travel downstream for tens or hundreds of kilometers.

Because wind has a much lower viscosity than water, it transports only sand, silt, and clay. Therefore, sand dunes and other wind-deposited sediments

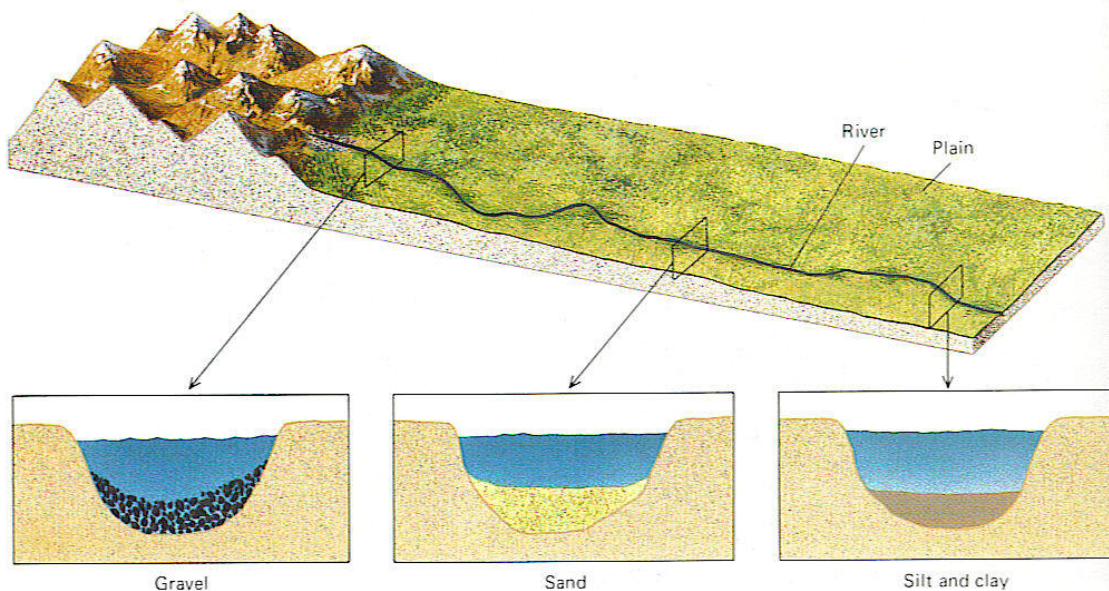
tend to be well sorted. Glacial ice, in contrast, has a high viscosity. Consequently, glaciers transport particles of all sizes together, from the coarsest boulders to the finest clay, and typically deposit **poorly sorted** sediment (Fig. 6-4). Thus, sorting is one criterion for determining how the sediment was transported and deposited.

## Deposition of Sediment

**Deposition** of clastic sediment occurs when transport stops, usually because the wind or water slows down and loses energy or, in the case of glaciers, when the ice melts. Deposition of dissolved ions occurs when they precipitate directly from solution or are extracted from solution by an organism to form a shell or skeleton.

Deposition of sediment occurs in a wide variety of geological environments. Streams deposit clastic sediment in streambeds, on floodplains adjacent to the streambeds, and on deltas where they enter lakes or the ocean. Clastic sediment deposited in ocean or lake environments may be redistributed by currents. Sand and silt may be deposited on land surfaces by wind to form dunes. Glaciers deposit large volumes of clastic sediments where they melt. Calcium dissolved in streams may be carried to a reef

Figure 6-3 The steepness of a stream usually diminishes in the downstream direction. Large particles are deposited in the mountains and along the mountain front and smaller ones are deposited on the nearly level plain.





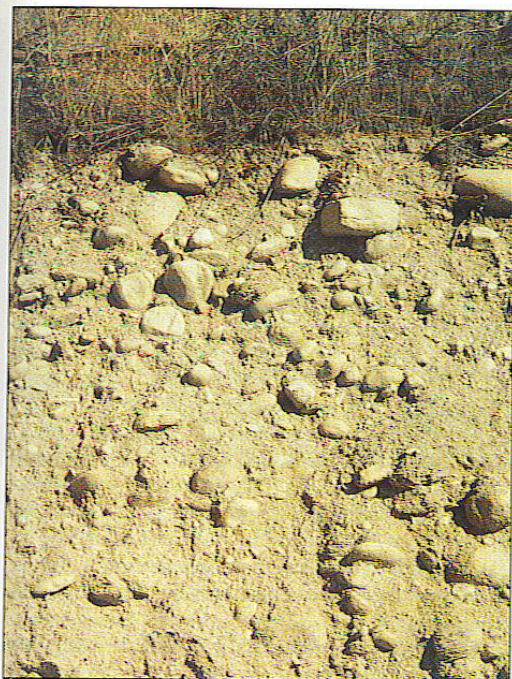


Figure 6-4 Poorly sorted sediment deposited by a glacier. Note that the cobbles are separated by finer sand, silt, and clay.

in the ocean where it is assimilated by clams, oysters, and corals to form shells and other hard parts composed of calcite. When the organisms die, the hard parts contribute to the growing pile of sediment around the reef.

Any setting in which sediment is deposited is called a **depositional environment**. One of the primary objectives of geologists who study sedimentary rocks is to use evidence found in the rocks, such as the roundness and sorting of grains, to interpret how the sediment was transported and the environment in which it was deposited.

### Lithification of Sediment

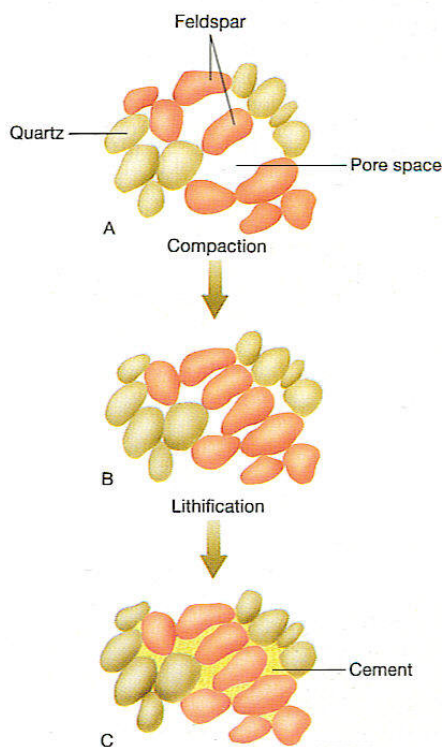
As mentioned earlier, lithification refers collectively to all the processes that convert loose sediment to hard rock. For most clastic sediments, the two most important types of lithification are compaction and cementation.

With the exception of a few perfect geometrical shapes, such as cubes, no collection of particles can completely fill its container. If you fill a measuring cup to the brim with marbles or sand, you can still

add a substantial amount of water. The amount of water that can be added is a measure of the empty space or **pore space** between the marbles or sand grains. The pore space is simply the voids between the grains (Fig. 6-5A). Most clastic sediment consists of particles separated by pore space. When sediment is deposited in water, the pore space is usually filled with water. The proportion of space occupied by pores depends upon particle size, shape, and sorting. Commonly, freshly deposited clastic sediment has about 20 to 40 percent pore space, although there are some notable exceptions. A well-sorted and well-rounded sand may have up to 50 percent pore space. Clay-rich muds may have as much as 90 percent pore space occupied by water.

As more layers of sediment accumulate, the weight of the overlying layers compresses the buried

Figure 6-5 (A) Pore space is the open space between grains of sediment. (B) Compaction reduces pore space and lithifies sediment by interlocking the grains. (C) Cement fills pores and lithifies sediment by binding grains together.





sediment. The pore space shrinks and some of the water is forced out (Fig. 6-5B). This process is called **compaction**. If the clastic particles have platy shapes, as in clay and silt, compaction alone may result in weak lithification because platy grains interlock like pieces of a puzzle.

As sediment undergoes burial and compaction, water normally circulates through the remaining pore space. This water commonly contains dissolved calcium carbonate, silica, and iron. The dissolved materials precipitate in the pore spaces, partially or completely filling them, and cementing the clastic grains firmly together to form a hard rock (Fig. 6-5C). This process is **cementation**. In some instances, the cement forms by chemical dissolution of minerals in the immediate environment. Alternatively, these materials may have come from great distances, traveling with groundwater through interconnecting pore spaces. Calcite, quartz, and iron oxides are the most common cements in sedimentary rocks.

Dissolved ions are commonly used by organisms in the ocean to build shells and other hard parts, as mentioned earlier. In some rather special environments, however, dissolved material becomes so concentrated that it precipitates directly from solution. The rocks formed by this process, called **crystallization**, have textures consisting of interlocking grains, like a three-dimensional jigsaw puzzle (Fig. 6-6). As the individual crystals grow from solution, they interlock with each other to produce grain boundaries like those of igneous rocks. The interlocking grain boundaries result in solid rock, even though the rock may never have experienced compaction or cementation. Very large deposits of halite (table salt) and some limestones form by crystallization.

The amount of time required for lithification of loose sediment varies greatly; it depends mainly on the availability of cementing material and water to carry the dissolved cement through the sediment. In some intensively irrigated areas of southern California, rock-hard caliche has cemented soils within

a few decades. In the Rocky Mountains, some glacial deposits less than 20,000 years old are cemented by calcium carbonate. In contrast, some sands and gravels deposited between 30 and 40 million years ago in southwestern Montana can still be dug with a hand shovel.

## 6.2 Types of Sedimentary Rock

Sedimentary rocks are broadly divided into three categories based on the type of sediment they are made of.

1. **Clastic sedimentary rocks** are composed of fragments of preexisting rocks that have been physically transported and deposited. Although most clastic particles form by mechanical weathering, this category includes rocks composed of tiny grains of clay minerals formed by chemical weathering. It also includes rocks made up of broken shells and other organic fragments, called **bioclastic rocks**.
2. **Organic sedimentary rocks** consist of the lithified remains of plants or animals. Bioclastic rocks fall into this category as well as the preceding one.
3. **Chemical sedimentary rocks** form by direct precipitation, or crystallization, from solution.

Limestone and dolomite are sedimentary rocks that can form by all three of the above processes and are discussed separately.

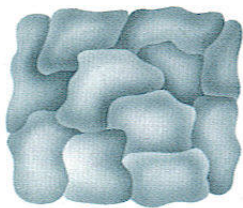
### Clastic Sedimentary Rocks

Clastic rocks are by far the most abundant of the three types, accounting for more than 80 percent of all sedimentary rocks. Table 6-1 shows that clastic rocks are classified primarily according to size of the particles or **clasts** that form them. The clasts may be rock fragments or mineral grains.

#### Conglomerate and Breccia

**Conglomerate** (Fig. 6-7A) and **breccia** (Fig. 6-7B) are coarse-grained clastic rocks. They are the lithified equivalents of gravel and rubble, respectively. In conglomerates the particles are predominantly rounded, and in sedimentary breccias they are angular. Large particles become rounded rapidly over short distances of transport, so sedimentary breccias are only found close to the weathering site where the angular rocks formed.

Figure 6-6 Rocks that precipitate from solution have interlocking grains.







A



B

Figure 6-7 (A) Conglomerate is lithified gravel. (B) Sedimentary breccia is lithified rubble. (Courtesy of Harold Levin.)

In conglomerates and sedimentary breccias, each clast is usually much larger than the individual mineral grains forming the clast. Therefore, the large clasts retain most of the characteristics of the original rock, and it is relatively easy to identify the parent rock. If enough is known about the geology of the area where conglomerates or sedimentary breccias are found, it is often possible to identify exactly where the clasts originated. A granite cobble found within a conglomerate must have come from nearby granite bedrock that was exposed to weathering and erosion.

Conglomerates typically have large pores between the clasts because the individual particles are large. These pores usually fill with finer sediment such as sand or silt trapped in the spaces among the large particles. The next time you walk along a cobbly stream look carefully between the cobbles. You will probably see a good example of fine clastic sediment trapped among the larger clasts.

### Sandstone

**Sandstone** consists of lithified sand grains. As mentioned in the previous chapter, of the abundant minerals in the Earth's crust, quartz is the most resistant to both chemical and mechanical weathering. Feldspar and the other common minerals are more susceptible to chemical decomposition in the weathering environment and to physical abrasion during transport. In contrast, about all that happens to quartz grains during weathering and transport is that they become rounded. Consequently, most sandstones consist predominantly of rounded grains of quartz. The only types of sandstone that contain

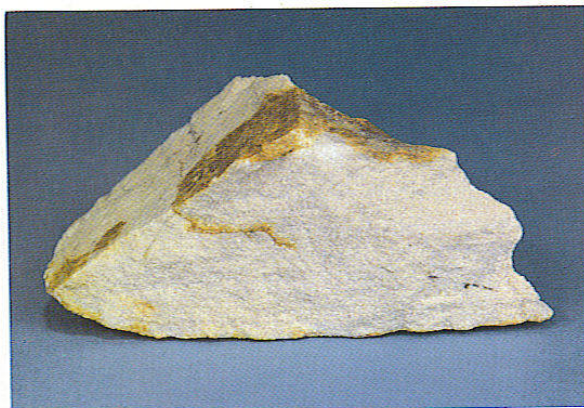
large proportions of feldspar or other minerals besides quartz are those deposited close to the weathering site where the sand grains formed. In these instances the sand was not transported far enough to eliminate the more easily weathered minerals. Because the grains making up most sandstones have been transported considerable distances, they tend to be well sorted, that is, all of the grains are about the same size.

Different types of sandstone are distinguished on the basis of mineral content. The word *sandstone*, used without qualifiers, refers to any clastic sedimentary rock comprised primarily of sand-sized grains. For the reasons just described, most sandstones consist predominantly of quartz. **Quartz sandstone** contains more than 90 percent quartz

Sandstone buttes in Monument Valley, Arizona.







A



B

Figure 6-8 (A) Quartz sandstone by definition contains more than 90 percent quartz grains. (Courtesy of Geoffrey Sutton.) (B) Arkose is a sandstone with more than 25 percent feldspar grains. The grains are commonly angular. (Courtesy of Geoffrey Sutton.)

(Fig. 6-8A). **Arkose** is a sandstone composed of 25 percent or more feldspar grains, with most of the remaining grains being quartz (Fig. 6-8B). The sand grains in arkose are commonly coarse and angular. The high feldspar content and the coarse, angular nature of the grains indicate that arkose forms only a short distance from its source area, perhaps adjacent to cliffs of granite or some other parent rock capable of supplying quantities of feldspar and quartz (Fig. 6-9).

**Graywacke** (Fig. 6-10A) is a poorly sorted sandstone with considerable quantities of silt and clay in its pores (Fig. 6-10B). Graywackes are

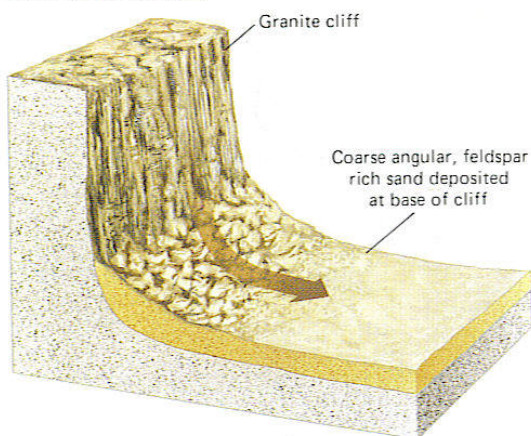
commonly dark in color because of the fine clay that coats the sand grains. The grains are usually quartz, feldspar, and fragments of volcanic, metamorphic, and sedimentary rock.

#### Claystone, Shale, Mudstone, and Siltstone

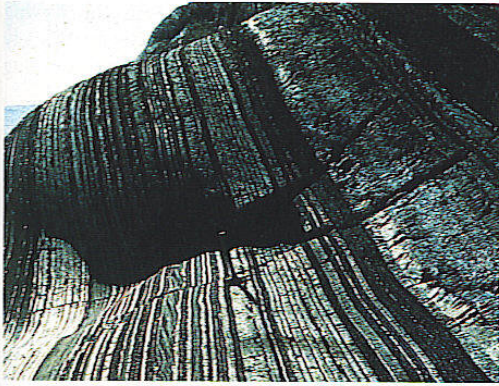
Claystone, shale, mudstone, and siltstone are all fine grained clastic sedimentary rocks. **Claystone** is composed predominantly of clay minerals and small amounts of quartz and other minerals of clay size. **Shale** (Fig. 6-11A) consists of the same material as claystone, but it has a finely layered structure called **fissility** along which the rock splits easily (Fig. 6-11B). Clay minerals have platy shapes, like the micas. When clays are deposited in water, the water content of the sediment is commonly 50 to 60 percent and can be as high as 90 percent. When first deposited, the plate-like clay minerals are randomly oriented, as shown in Figure 6-12A. As more sediment accumulates on top of the first layer, compaction occurs, driving out most of the water and causing the clay plates to rotate so that their flat surfaces are perpendicular to the pull of gravity (Fig. 6-12B). Thus, they stack like dishes on your shelf or like sheets of paper. The clay grains interlock as they compact to form a moderately well lithified shale. The fissility of shales results from the parallel orientation of the platy clay minerals.

More than 75 percent of all clastic sedimentary rocks and over half of all sedimentary rocks are shales (Fig. 6-13). The abundance of shale is a direct reflection of the vast quantities of clay produced by weathering:

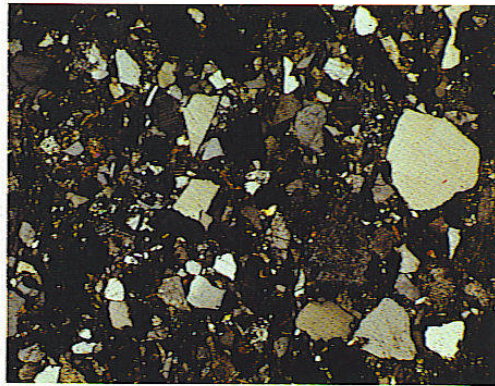
Figure 6-9 Arkose commonly accumulates close to the source of the sediment.







A



B

Figure 6-10 (A) Graywacke is a dark, poorly sorted sandstone. (Courtesy of P. Hoffman.) (B) This photomicrograph shows silt and clay filling the pore spaces between the sand grains in graywacke. (Courtesy of Harold Levin.)

Figure 6-11 (A) An outcrop of shale. (B) Shale is a thinly layered rock mostly made up of clay minerals. The finely layered structure, called fissility, is shown in this close-up view.

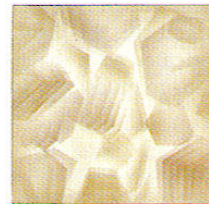


A



B

Figure 6-12 (A) Randomly oriented clay particles in freshly deposited mud. (B) Parallel clay particles after compaction and dewatering by weight of overlying sediment.



A

Compaction



B



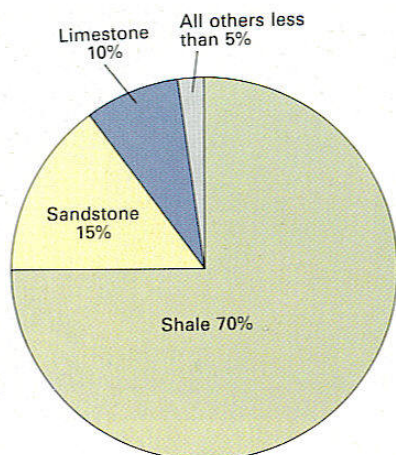


Figure 6-13 Relative abundances of sedimentary rock types.

Shale is usually gray to black in color due to the presence of partially decayed remains of plants and animals commonly deposited with clay-rich sediment. This organic material in shales is the source of most oil and natural gas. (Discussed in Chapter 21.)

**Mudstone** is a nonfissile rock composed of a mixture of clay and silt. During compaction of some mixtures of clay and silt, the platy minerals are not as effectively reoriented as in shales, resulting in the lack of fine layering in mudstone. In some mudstone

and claystone, layering is absent because burrowing animals such as worms, clams, and crabs completely disrupted it by churning the sediment as they dug looking for food.

**Siltstone** is lithified silt. The main component of most siltstones is quartz, although clays are also commonly present. Siltstones often show layering, but lack the fine fissility of shales because of their lower content of platy minerals.

### Organic Sedimentary Rocks

Organic sedimentary rocks such as chert and coal form by lithification of organic sediments.

#### Chert

**Chert** is a rock composed of pure quartz. It occurs in two forms: as sedimentary beds interlayered with other sedimentary rocks and as irregularly shaped lumps called **nodules** (Figure 6-14), which occur within other sedimentary rocks. Microscopic examination of the bedded variety often shows that it is made up of the remains of tiny marine organisms that make their skeletons of silica rather than calcium carbonate. In contrast, nodular chert appears to form by inorganic precipitation from silica-rich groundwater, most often in limestone.

#### Coal

**Coal** is the lithified remains of plant material. When plants die, their remains usually decompose by reaction with oxygen. However, in vast swamps in warm climates and in other environments where

Figure 6-14 (A) Dark-colored bedded chert interlayered with light-colored limestone. (Courtesy of USGS, D. A. Brew.) (B) Red chert nodules in light-colored limestone.







Ridges of salt on Bonneville Salt Flats, Utah. (Courtesy of Tom Till.)

plant growth is extremely fast, dead plants can accumulate so rapidly and in such great quantities that the oxygen available in the accumulating pile of debris is used up long before the decay process is complete. The undecayed or partially decayed plant remains form a material called **peat**. As peat is buried and compacted by overlying sediments, it converts to coal, which is a hard, black, combustible rock that commonly contains abundant plant fossils.

### Chemical Sedimentary Rocks

Recall from the previous chapter that some elements in rocks and minerals, such as calcium, sodium, potassium, and magnesium dissolve during chemical weathering. Those dissolved ions are transported by groundwater and streams to the oceans or to saline lakes such as Great Salt Lake of Utah. **Evaporites** are chemically precipitated sedimentary rocks. They form when evaporation of water concentrates dissolved ions to the point where they begin to precipitate from solution. The most common minerals found in evaporite deposits are **gypsum** ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ )<sup>1</sup> and **halite** ( $\text{NaCl}$ ). Evaporites are uncommon and comprise only a small proportion of all sedimentary rocks. One other important chemical sedimentary rock is discussed in the next section on carbonate rocks.

<sup>1</sup> The  $2\text{H}_2\text{O}$  in the chemical formula of gypsum means there is water incorporated into the mineral structure.

### Carbonate Rocks: Limestone and Dolomite

**Carbonate rocks** are those made up primarily of carbonate minerals. Recall from Chapter 2 that carbonate minerals contain the carbonate ion,  $\text{CO}_3^{2-}$ . The most common carbonate minerals are **calcite** (calcium carbonate,  $\text{CaCO}_3$ ) and **dolomite** (calcium magnesium carbonate,  $\text{CaMg}(\text{CO}_3)_2$ ). Calcite-rich carbonate rocks are called **limestone**, whereas rocks rich in the mineral dolomite are also called **dolomite**. Some geologists use the term *dolostone* for the rock name to distinguish it from the mineral dolomite.

Seawater is very close to being saturated with dissolved calcium carbonate. That is, if calcium carbonate were slightly more concentrated in the oceans, it would precipitate spontaneously to form calcite. Clams, oysters, corals, some types of algae, and a tremendous variety of other marine organisms make their shells and other hard body parts of calcium carbonate. Because calcium carbonate is so concentrated in seawater, animals and plants that secrete calcite thrive and multiply in tremendous numbers, particularly in warm, shallow parts of the oceans where especially favorable conditions for life are found. Most limestones simply consist of the lithified remains of those marine organisms.

Often waves or ocean currents break up and transport fragments of shells, corals, and other marine organisms to form clastic sediment. A rock



formed by lithification of such sediment is called **bioclastic limestone**, indicating its two-step mode of origin including both biological and clastic processes. Most limestones are bioclastic in origin. Bioclastic rocks fit equally well into both the clastic and organic classes of sedimentary rocks. **Coquina** is a fairly common bioclastic limestone consisting wholly of coarse shell fragments cemented together (Fig. 6-15). **Chalk** is a very fine grained, soft, earthy, white to gray bioclastic limestone made of the shells and skeletons of microorganisms that spend their lives floating near the surface of the oceans. When they die, their remains sink to the bottom and accumulate to form chalk. The famous White Cliffs of Dover in England are made of chalk.

Calcium carbonate is so close to saturation in seawater that it can precipitate under the proper conditions. One of the most spectacular examples of chemical precipitation of calcium carbonate occurs today on the shallow Bahama Banks, south of Bimini in the Caribbean Sea. Waves and currents roll tiny shell fragments back and forth on the sea bottom as calcium carbonate precipitates in spherical layers on the fragments. As a result, small, nearly perfect spheres called **ooids** grow. These spheres of calcium carbonate can later become cemented to form **oolitic limestone**. Figure 6-16A shows underwater dunes of ooids on the Bahama Banks. Figure 6-16B is a microscopic view of a very thin slice of oolitic limestone showing concentric layers of calcium carbonate that added on as the ooids grew. Limestone of this type falls properly into the category of chemical sedimentary rocks.

Figure 6-15 Coquina is bioclastic limestone consisting of cemented shell fragments. (Courtesy of Geoffrey Sutton.)



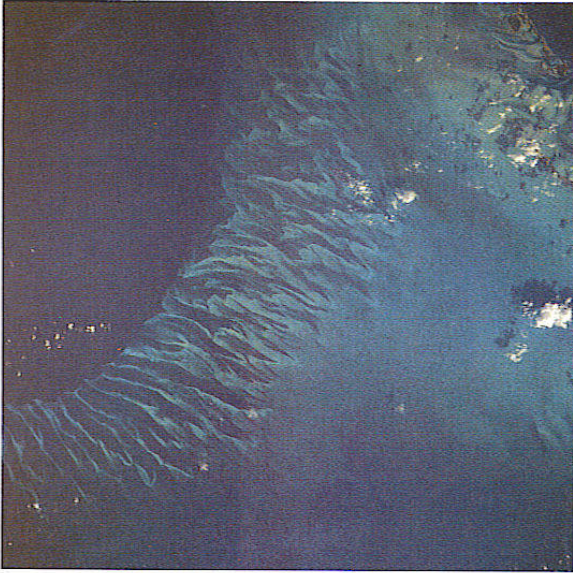
White Cliffs of Dover. (Courtesy of British Tourist Agency.)

Organisms that form carbonate sediments and rocks thrive and multiply in warm shallow seas. Shallow water is favorable because the sun shines directly on the ocean floor, where most of them live. Therefore, carbonate rocks form in the greatest abundance in shallow water along coastlines at low and middle latitudes. They also form in great quantities on continents when a rise in sea level floods surfaces of continents with shallow seas. (Marine flooding of continents is discussed more in Chapter 13.)

The rock dolomite is widespread. It comprises over half of all carbonate rocks more than a billion years old, and a smaller, although substantial, proportion of younger carbonate rocks. However, there is no place in the world today where dolomite can be observed in the process of forming in large amounts. Since it is so abundant in ancient rocks, we would expect dolomite to make up a large proportion of the carbonate sediments that are forming today; yet, it doesn't. Only in a very few places, such as the Florida Keys and the Bahama Islands, is dolomite known to be actively forming, and in those places it forms only in small amounts. This dilemma is known among geologists as **the dolomite problem**, and it has been the cause of a tremendous amount of field and laboratory research.

The general consensus among geologists is that most dolomite does not form as a primary sediment or rock. Instead, it forms as magnesium-rich solutions derived from seawater percolate through beds of existing limestone. As the solutions make their way through the limestone, magnesium ions replace half of the calcium in the calcite, converting the limestone beds to dolomite.





A

The Dolomites, a mountain range in Austria and northern Italy, are made up mostly of the rock, dolomite. (Courtesy of Italian Tourist Agency.)



B

Figure 6-16 (A) Underwater dunes of ooids forming today on the Bahama Banks. The dunes form as currents sweep the ooids along the shallow sea floor. (Courtesy of NASA.) (B) A microscopic view of oolitic limestone showing growth rings and calcium carbonate cement between the ooids. (Courtesy of Don Winston.)





### 6.3 Sedimentary Structures

Nearly all sedimentary rocks contain features called **sedimentary structures** that develop as sediment is deposited or after deposition but before sediment becomes lithified. Sedimentary structures often contain important clues that help in identifying how sediments were transported and what type of geological environments they were deposited in.

The most obvious and widespread sedimentary structure is **bedding** or **stratification** (Fig. 6-17). Bedding is layering that develops as sediments are deposited. It may result from differences in texture, mineral composition, color, or cementation between the layers. Most sedimentary beds were originally horizontal because most sediment is deposited on nearly level surfaces.

As sand is transported by flowing water or blowing wind, it tends to heap up in parallel ridges. Currents carry the sand grains up the upstream side of the ridge. When they reach the top, the grains tumble down the steeper downstream side, forming asymmetrical sand ridges or dunes with their steep sides toward the downstream direction (Fig. 6-18A). **Ripple marks** are small, nearly parallel ridges and troughs formed in loose sand by moving water or wind. If wind forms waves in a standing body of shallow water, the back and forth motion of the waves forms symmetrical ripple marks in bottom sand (Fig. 6-18B). Ripple marks are often preserved in sandy sedimentary rocks (Fig. 6-19).

Figure 6-18 (A) Asymmetrical ripple marks form when wind or currents move continuously in the same direction. (B) Symmetrical ripple marks form when waves oscillate back and forth.

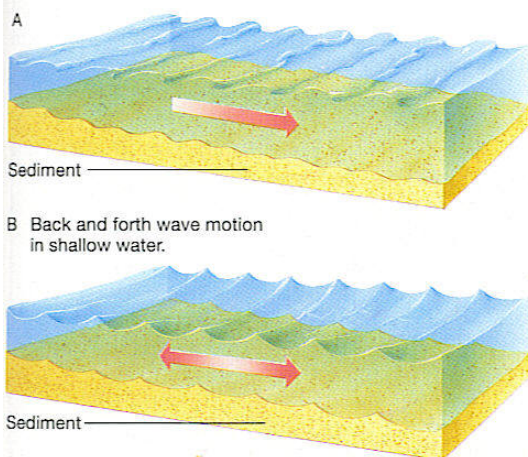


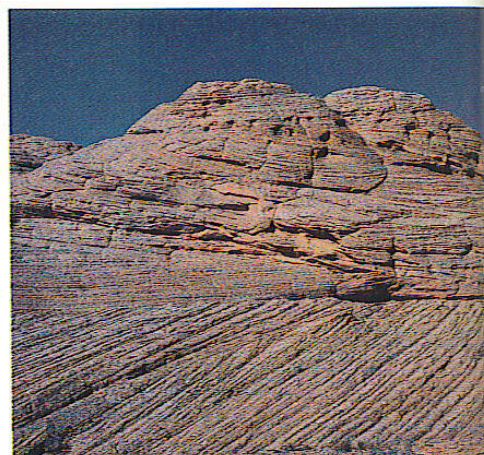
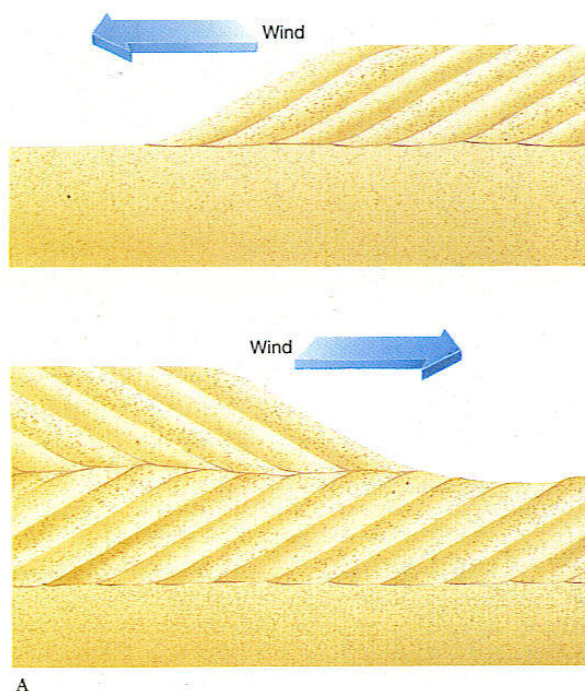
Figure 6-19 Ripples preserved in sandstone. The different orientations of the ripples show that the current direction changed as successive layers of sand were deposited. (Courtesy of Larry Davis.)

**Cross-stratification**, often called simply **cross-bedding**, consists of an arrangement of small beds at an angle to the main sedimentary layering (Fig. 6-20A). A **sand dune** is a large-scale version of a ripple, described in the previous paragraph. Figure 6-20B shows that cross-beds are the preserved layering formed by sand grains tumbling down the steep, downstream face of a dune or ripple mark. Cross-bedding forms in both windblown and water-transported sediments in a variety of environments on both large and small scales, but it invariably indicates transport and deposition by a flowing medium (water currents or blowing wind). Further, because cross-bedding indicates the direction in which the current was flowing, it is often used to infer the direction of sediment transport.

**Graded bedding** is a type of bedding in which each layer shows decreasing particle size from bottom to top (Fig. 6-21). Graded beds commonly form when poorly sorted sediment settles to the bottom of a body of water. Thus, they form only when some violent activity suddenly mixes a wide range of clastic grain sizes together in standing water. The larger grains settle rapidly and concentrate at the base of the bed. Finer particles settle more slowly and accumulate in the upper parts of the bed.

**Mudcracks** are polygonal cracks that form in mud when the sediment shrinks as it dries (Fig. 6-22). Mudcracks indicate alternating coverage by water followed by a drying cycle when the surface was exposed to air. An example of such an environment is an intertidal mudflat, where the sediment is flooded by water at high tide and exposed at low

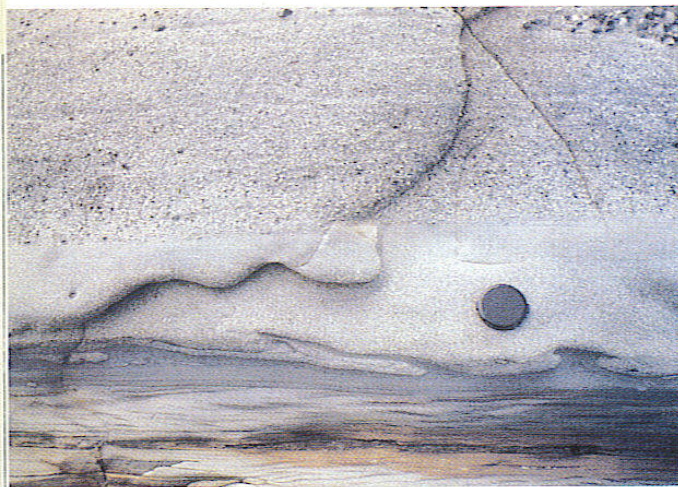




B

Figure 6-20 (A) The development of cross-bedding in sand deposited by water or wind currents. (B) Cross-bedding in lithified sand dunes in southern Utah.

Figure 6-21 This photo shows three graded beds. Notice that the size of the grains in each bed becomes finer higher in the bed. The lens cap is in the middle bed. Above is the coarse-grained bottom of another bed and below is fine black silt of a third graded bed. (Courtesy of Educational Images, Bern Aarons.)



tide. The cracks often fill with sediment carried in by the next flooding event (perhaps the next high tide) and are commonly well preserved in rocks.

Occasionally, very delicate sedimentary structures are preserved in rocks. Geologists have found the imprint of a single raindrop that fell on a muddy surface about 1 billion years ago and the imprint of a cubic salt crystal that formed as a puddle evaporated. Mudcracks, raindrop imprints, and salt crystal imprints all show that the sediment containing them must have been deposited in shallow water and that the sediment surfaces were intermittently exposed to air.

**Fossils** are any remains or traces of a plant or animal preserved in rock—any evidence of past life. Fossils are sedimentary structures, and are discussed in detail in Chapter 8.

## 6.4 Interpreting Sedimentary Rocks: Depositional Environments

Imagine that you are hiking in the hills or mountains and come across an outcrop of shale. Entombed in the shale you find a few fossils of marine clams of





Figure 6-22 Mudcracks form when wet mud dries and shrinks.

a type that lived in shallow water environments. Therefore, you interpret that the shale must have originally been mud deposited in a shallow sea. Further, since the outcrop of shale is now well above sea level, you infer that this portion of the continent must have been uplifted to form the hills or mountains.

Geologists study sedimentary rocks to help understand the past. Here are some key questions geologists ask when studying sedimentary rocks. Where did the sediment originate? What was the climate like when the sediment and rock formed? Was the sediment transported by flowing water, wind, or by a glacier? Was it deposited in the ocean

Delicate raindrop imprints formed by rain that fell about a billion years ago on a mudflat. (Courtesy of Ken Bogle.)



The imprints of salt crystals formed as a puddle evaporated on a mudflat about a billion years ago. (Courtesy of Ken Bogle.)





or on a continent? If it was deposited in the ocean, was it on a beach, on shallow offshore mudflats, or in deep water? If it was deposited on a continent, was it in a lake, a streambed, or a flood plain? Questions such as these are answered by analyzing the mineralogy, textures, and sedimentary structures of sedimentary rocks. Additionally, the size and shape of a sedimentary rock unit contain clues to its depositional environment. Accurate interpretations of depositional environments are often rewarding because valuable concentrations of oil and gas, coal, and metals form in certain types of environments.

Recall from Chapter 1 that one expression of Hutton's law of uniformitarianism is "The present is the key to the past." The same processes that form the minerals, textures, and structures of sediments today are those that formed sedimentary rocks long ago. Uniformitarianism tells us that we should look at sediments and rocks forming today, in modern depositional environments, to understand the processes that formed rocks in the past.

Sedimentary depositional environments vary greatly in scale, from large-scale environments such as an entire ocean basin to small-scale environments such as a 3-meter-long gravel bar in a little stream. Many small-scale environments may be active within a single large-scale depositional system (Fig. 6-23).

## Large-Scale Marine Environments

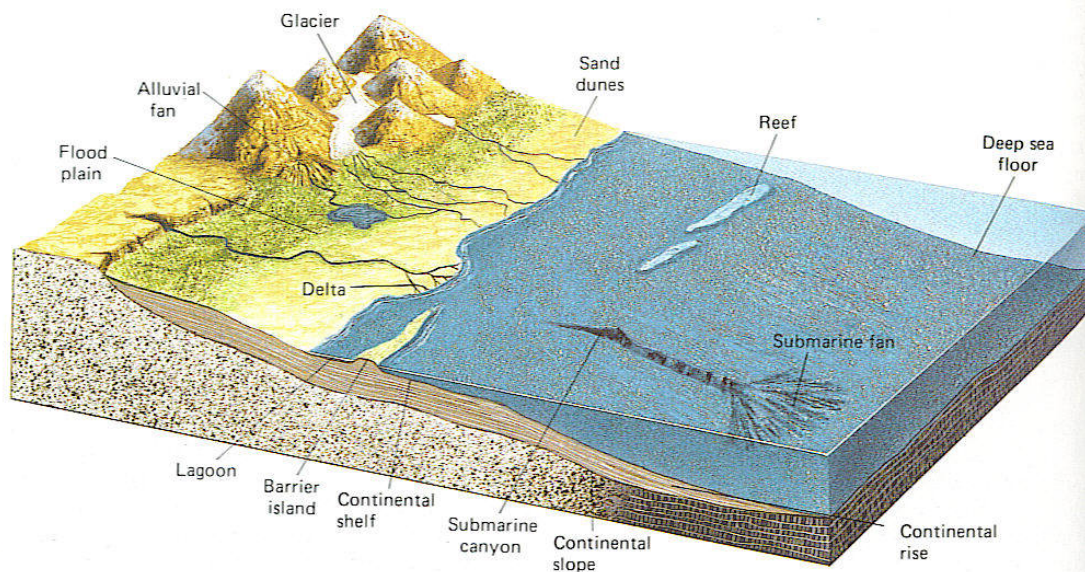
Large-scale marine environments include continental margin basins, continental shelves, continental platforms, intracratonic basins, and deep ocean basins.

### Continental Margin Basins

The largest proportion of all sediment is transported and deposited by the world's great rivers, such as the Amazon, Nile, and Mississippi. All major rivers empty into the oceans, where their currents slow and lose energy. When a river loses energy as it enters the ocean, its load of sediment falls out and accumulates to form a broad, flat plain called a **delta**. Recall that streams sort sediments. Most large boulders, cobbles, and even pebbles are left behind at the mouths of mountain canyons where the streams start to level off. Therefore, deltas are composed of finer sediments, including sand, silt, and clay.

So much sediment accumulates in a large delta system that the weight cannot be supported by the underlying lithosphere. As a result, the delta sinks under its own weight. The lithosphere continues to sink as additional sediment accumulates. The sinking lithosphere produces a continuously deepening **continental margin basin**. Most of the world's supply

Figure 6-23 Common small-scale depositional environments.





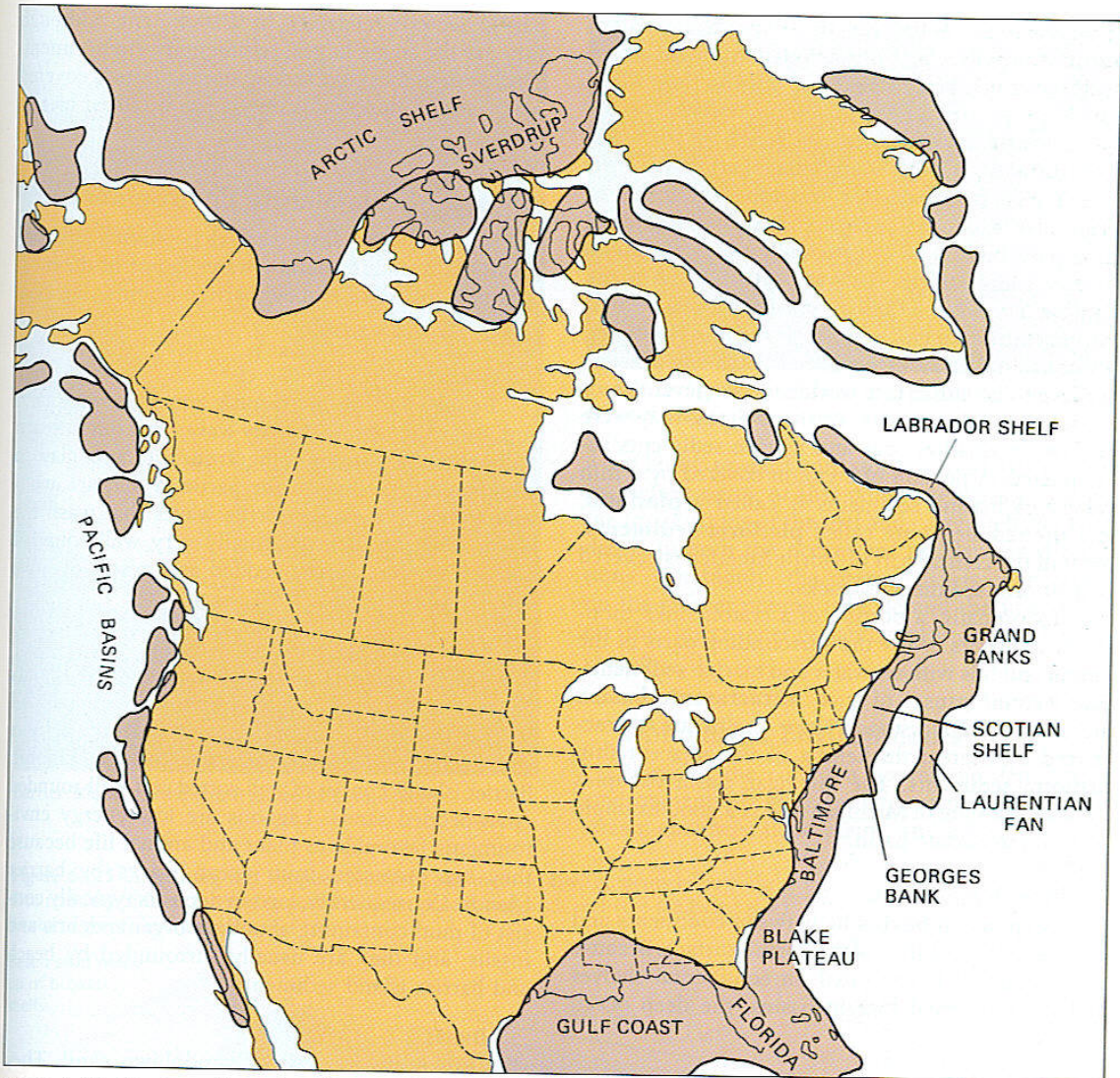


Figure 6-24 Continental margin sedimentary basins surround North America. (Modified from Bill St. John.)

of sediment is eventually deposited in such basins at the mouths of major rivers. Figure 6-24 shows major areas of sediment accumulation in continental margin basins and on continental shelves in North America.

As an example of the scale of a large delta and continental margin basin, deltaic sediment deposited by the Mississippi River covers an area larger than 2 million square kilometers and in places is more than 8 kilometers thick.

### Continental Shelves

**Continental shelves** are shallow, nearly level areas of continental crust that are submerged below sea level at the edge of continents. A continental shelf may extend outward from the shore for several hundred kilometers, although its depth is typically less than 200 meters. Ocean currents commonly carry sediment parallel to coastlines away from the mouths of rivers and streams, depositing them widely over continental shelves. A broad continental shelf



runs along the entire length of the east coast of North America, where the sedimentary rocks of the shelf contain substantial oil and gas reserves.

### Platform Sediments

**Cratons** are parts of continental crust that have been tectonically stable for very long times; that is, they have not been involved recently in folding, mountain building, or igneous activity. A craton usually comprises the largest part of a continent. Cratons normally lie above sea level because they are continental crust. At times in the past, however, portions of all cratons have been submerged below sea level, due either to a worldwide sea level rise or to sinking of the cratons. At those times, they were covered by shallow seas and marine sediments accumulated. A portion of a craton covered by a thin veneer of marine sediments is called a **platform**, and the sediments are called **platform sediments**. Most of the central part of North America is covered by platform sedimentary rocks.

Occasionally, a portion of a craton sinks thousands of meters below the surrounding parts of the craton and fills with seawater and marine sediments. The tectonic causes of such **intracratonic basins** are not well understood. These basins are characterized by a great thickening of the adjacent thin platform sediments. The Michigan Basin occupies most of the state of Michigan and is a good example of an intracratonic basin.

### Deep Ocean Basins

**Deep ocean basins** lie between continents and cover about two-thirds of the Earth's surface. Because most sediment is deposited on continental shelves and in continental margin basins, the deep ocean

basins receive relatively little sediment, although they are the single largest sedimentary environment. The basalt of most of the deep ocean floors is covered by a layer of mud that is only a few hundred meters thick.

### Small-Scale Marine Environments

Many common small-scale depositional environments are found in shallow water. Some of the most common include beaches, barrier islands, lagoons, and reefs.

#### Beaches

**Beaches** are gently sloping zones between land and water that are washed by waves and tides. Beach sediments can be anything from silt and clay to boulders, depending on the particles that are available and on the energy of the waves that wash the beach. The sediment is usually very well rounded and is commonly cross-bedded as a result of wave action and currents.

#### Barrier Islands

**Barrier islands** are long, narrow sand islands constructed by waves and currents. They run parallel to the shoreline and are separated from it by a shallow, protected body of water called a **lagoon**. Barrier islands consist of well-sorted and well-rounded cross-bedded sands. Lagoons are low energy environments favorable to plant and animal life because they are protected from ocean waves by barrier islands. Consequently, lagoon deposits typically consist of mud containing abundant organic debris and fossils, and they are usually surrounded by beach and barrier island sediments.

#### Dunes

**Dunes** are mounds of windblown sand. They form where there is wind and an abundant supply of sand, both of which are present on beaches and barrier islands. Thus, dunes are common on beaches and barrier islands. Dunes are characterized by steep cross-bedding and very well sorted sand. Cape Cod, Long Island, and the Oregon and Washington coast have abundant sand dunes. Dunes also form in desert environments (see Chapter 19 for more on desert dunes).

#### Reefs

**Reefs** are submarine mounds that consist of the remains of corals, algae, and other organisms with hard shells. As a result, reef deposits lithify to form limestone. As the organisms grow, multiply, and die

Muir beach, California.







Barrier Island on the south shore of Long Island.



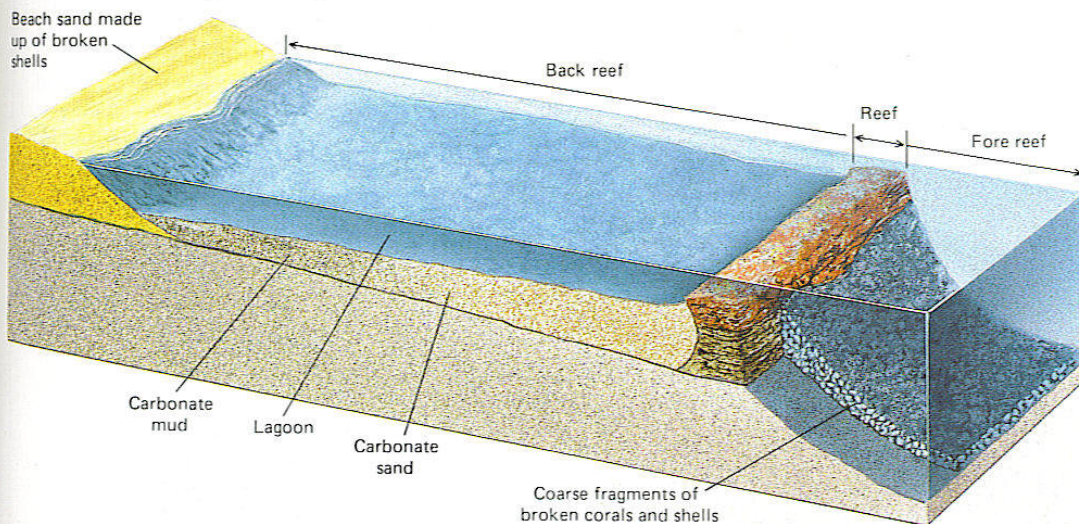
Castle coral growing on a reef in approximately 8 meters of water, Papua, New Guinea. (Courtesy of Larry Davis.)

a reef builds upward until storm waves begin eroding its highest parts. At that point, the waves break off the top portions of the reef and carry shell and coral debris in both the oceanward and landward directions. Commonly, the coarser debris concentrates on the steeper oceanward side and the finer debris on the lower energy landward side of the reef (Fig. 6-25).

### Nonmarine Environments

Some of the common nonmarine depositional environments are glacial environments, alluvial fans, stream channels, flood plains, and lakes.

Figure 6-25 A growing reef supplies bioclastic sediment to environments in both the fore reef (the side of the reef exposed to open ocean) and back reef (the landward side) as storm waves break up the reef top.





### Glacial Environments

Glaciers are massive sheets of ice as much as three kilometers thick that move slowly over the landscape. They can carry large quantities of sediment, which are deposited as the ice melts. As previously mentioned, ice can carry both large and small particles, with little distinction between the two. As a result, glacially deposited sediment is typically poorly sorted and commonly includes a mixture of sizes from clay to boulders.

### Alluvial Fan Environments

**Alluvial** sediment is deposited by a stream or other flowing water. As a stream flows out of a mountain front into a valley, its steepness and velocity decrease. Therefore, it loses energy and deposits large amounts of sediment in fan-shaped mounds called **alluvial fans** that spread out from the mountain front onto the valley floor. Alluvial fan deposits are commonly coarse sands and gravels that show poor to moderate sorting. Alluvial fans characteristically form in arid to semiarid environments.

### Stream Channel and Floodplain Environments

Most sediment transported by a stream is carried during a few days each year, usually in spring, when the stream is in flood. During flooding, streams overflow their banks and some of the water flows over low, flat areas adjacent to the stream channel called the **floodplain** (Fig. 6-26). Water flows more slowly over the floodplain than in the channel. Consequently, the energy of the flowing water is lower, and only the finer sediment is carried onto the floodplain. The coarser sediment is transported

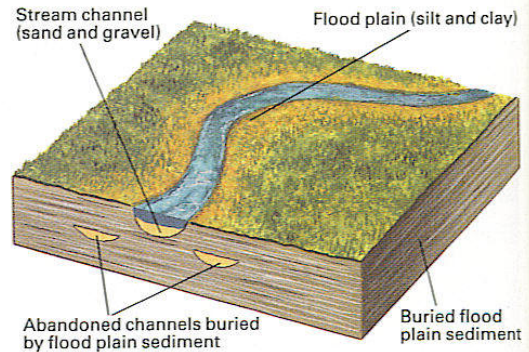


Figure 6-26 Coarse sediment is deposited in stream beds and finer ones are deposited in the adjacent floodplain.

in the channel where the flow is more rapid. As the flood wanes, the energy of flow in both the channel and floodplain decreases, and most of the sediment is deposited, where it remains until the next flood. The coarser sediment concentrates in the channel, and the finer on the floodplain.

### Lake Environments

Lake deltas are similar to ocean deltas (except for size) and consist of fine grained sediments. Lake bottom sediment typically consists of very fine grained clay and silt that remain in suspension in the water as it flows slowly outward beyond the delta. Lakes in arid or semiarid environments commonly dry up periodically, causing the deposition of evaporites.

Alluvial fan in Death Valley.





## SUMMARY

**Sedimentary rocks** cover about three-fourths of the Earth's land surface. **Sediment** is produced by weathering and includes all **clastic** particles transported and deposited by water, wind, glaciers, and gravity; the remains of organisms; and chemically precipitated minerals. Clastic sediments are named and classified according to particle size. Sedimentary rocks are **lithified** sediment.

**Water** is the most important agent of sediment transport. Clastic sediment becomes **rounded** and **sorted** during transport by water and wind. When transport ceases, sediment is **deposited**. Most sediment becomes lithified by **compaction** and **cementation**.

**Clastic sedimentary rocks** are composed of lithified clastic sediment and are named and classified primarily according to the size of the clastic grains. Common types are **conglomerate**, **sandstone**, **siltstone**, **shale**, and **claystone**. **Organic sedimentary rocks** are made up of the remains of organisms. **Coal** and **chert** are common organic sedimentary rocks. **Chemical sedimentary rocks** include **evaporites**, rocks that precipitate directly from solution as lake water or seawater evaporates. Deposits of

**halite**, **gypsum**, and other less abundant minerals form in this way. **Limestone** can form by clastic, organic, and chemical processes or by combinations of those processes. **Dolomite** is a carbonate rock in which half of the calcium in calcite has been replaced by magnesium.

**Sedimentary structures** are features that develop as sediments are deposited or after deposition but before lithification. They include all types of **bedding**, **ripple marks**, **mudcracks**, and **fossils**. Sedimentary structures contain vital clues regarding the modes of transport and deposition of sediments and the sedimentary environments in which they were deposited. The interpretation of **depositional environments** is one of the primary objectives of the study of sedimentary rocks. Depositional environments include all large- and small-scale geological environments, both marine and nonmarine, in which sediments are deposited. Marine environments include **deltas**, continental margins and shelves, submerged **cratons**, and deep ocean basins. Nonmarine environments include glaciers, **alluvial fans**, streams, and lakes.

## KEY TERMS

sedimentary rocks 131	pore space 135	coal 140	delta 148
lithification 132	cementation 136	peat 141	continental margin
sediment 132	clastic sedimentary	evaporites 141	basin 148
clastic sediment 132	rocks 136	gypsum 141	continental shelf 149
gravel 132	clasts 136	carbonate rocks 141	craton 150
rubble 132	conglomerate 136	dolomite 141	platform
pebbles 132	breccia 136	limestone 141	sediments 150
cobbles 132	sandstone 137	coquina 142	intracratonic
boulders 132	quartz sandstone 137	chalk 142	basins 150
sand 132	arkose 138	ooids 142	beaches 150
silt 132	graywacke 138	bedding 145	barrier islands 150
clay 132	claystone 138	stratification 145	lagoon 150
mud 132	shale 138	ripple marks 145	dunes 150
sorting 134	fissility 140	cross-bedding 145	reefs 150
deposition 134	mudstone 140	graded bedding 145	alluvial fan 152
depositional	siltstone 140	mudcracks 145	floodplain 152
environment 135	chert 140	fossils 146	



**REVIEW QUESTIONS**

1. Why do sedimentary rocks cover more than 75 percent of the Earth's land surface when they comprise only 5 percent of the volume of the continental crust?
2. Explain what is meant by *sediment*.
3. List the clastic sedimentary particles in order of decreasing grain size.
4. What is clay?
5. In what ways are clastic sediments modified during transport?
6. Why is the maximum size of particles transported by wind finer than the maximum size transported by streams?
7. Why is the maximum size of particles transported by glaciers coarser than the maximum size transported by streams?
8. Describe how loose clastic sediment becomes lithified to form hard rock.
9. What is pore space in a clastic sediment? How is it modified during lithification?
10. Why are sedimentary breccias uncommon?
11. Why are most sandstones made up predominantly of quartz?
12. In what geological environment does arkose form?
13. How do shales acquire "fissility"? Why do mudstones lack that property?
14. How do limestones form?
15. What is a bioclastic limestone?
16. How do dolomites form? What is the dolomite problem?
17. How does coal form?
18. How do evaporites form?
19. What does cross-bedding in a sandstone tell you about the depositional environment?
20. What do the presence of mudcracks in a mudstone tell you about the depositional environment?

**DISCUSSION QUESTIONS**

1. Field geologists sometimes come upon large sections of sedimentary rocks that have been turned upside down by tectonic activities. How would you use sedimentary structures to determine whether a sequence of sedimentary rocks is upright or overturned?
2. What can you infer about the transport history of the sand grains in a quartz sandstone containing more than 99 percent well-rounded quartz sand grains?
3. On a field trip you discover a sequence of sedimentary rocks composed of thin, black shales containing marine fossils interbedded with layers of gypsum and halite. What can you deduce about the depositional environment in which the sediments were deposited?
4. On another field trip you encounter a sequence of sedimentary rocks consisting of cross-bedded conglomerates in which the clasts are only moderately sorted but are well rounded. The conglomerates are interbedded with layers of cross-bedded arkose. The cross-bedding in both the arkose and conglomerate indicate transport from east to west. Granite clasts in the conglomerate are identical to granite outcrops found about 4 kilometers to the east. Describe the probable origin of the sediments and the sedimentary environment in which they were deposited.
5. Why is shale the most abundant sedimentary rock?
6. Would you expect to find large quantities of sedimentary rocks on the Moon? Why or why not? If you do expect to find them, what types would you expect?