12 River Systems

A river system is a network of connecting channels through which water, precipitated on the surface, is collected and funneled back to the ocean. At any given time, about 1300 km^3 of water flows in the world's rivers. As it moves, it picks up weathered rock debris and carries it to the oceans. Rivers are the dominant agents of erosion on our planet. No matter where you go, rivers have played some role in shaping the surface.

The tremendous waterfalls of the Iguassú River, shown in the panorama above, illustrate both the beauty and power of rivers. The river rises in a coastal mountain range hardly 50 km from the Atlantic Ocean. From its headwaters, it flows 700 km inland along the border of Argentina and Brazil before it joins the great Paraná River and empties into the Atlantic Ocean. Shortly before it merges with the Paraná, the river plunges over a series of high escarpments created by the flood basalts of the Paraná basin. With a torrential roar, the falls plunge over cliffs that are 3 km long and greater than 70 m high. More than 273 separate falls can be counted along the rugged cliffs.

But river systems also formed the gentle rolling hills of Ohio and Kansas, the levees and backswamps of Louisiana, the ridges and valleys of the Appalachian Mountains, and the flat coastal plains. No other geologic agent is so universally important in the origin and evolution of the surface upon which we live.

Rivers are ideal examples of natural systems. The energy that drives the flow of water ultimately comes from the Sun and from gravity. Moreover, it is easy to see that a river is an open system with multiple sources for water and for the sediment it carries. Water can come from melting snow and ice, from direct precipitation, from groundwater, and of course from other rivers. Sediment is added to the system by erosion and solution and eventually it leaves the system when it is deposited far from its source. This majestic system interacts with other parts of the hydrologic system and, as we shall see, is modified by the tectonic system in diverse ways. Rivers respond to climate change as well as to the motion of the continents.

In this chapter, we discuss the effects and controls on rivers as natural systems: how water flows and how it carries and eventually deposits sediment. We will also consider how the entire river system responds to changes.

MAJOR CONCEPTS

1. Running water is part of Earth's hydrologic system and is the most important agent of erosion. Stream valleys are the most abundant and widespread landforms on the continents.
2. A river system consists of a main channel and all of the tributaries that flow into it. It can be divided into three subsystems: (a) a collecting system, (b) a transporting system, and (c) a dispersing system.
3. The most important variables in stream flow are (a) discharge, (b) gradient, (c) velocity, (d) sediment load, and (e) base level.
4. The variables in a stream constantly adjust toward a state of equilibrium.
5. Rivers erode by (a) removal of regolith, (b) downcutting of the stream channel by abrasion, and (c) headward erosion.
6. As a river develops a low gradient, it deposits part of its load on point bars, on natural levees, and across the surface of its floodplain.
7. Most of a river's sediment is deposited where the river empties into a lake or ocean. This deposition commonly builds a delta at the river's mouth. In arid regions, many streams deposit their loads as alluvial fans at the base of steep slopes.
8. The origin and evolution of the world's major rivers are controlled by the tectonic and hydrologic systems.

GEOLOGIC IMPORTANCE OF RUNNING WATER

Running water is by far the most important agent of erosion. Other agents, such as groundwater, glaciers, and wind, are locally dominant but affect only limited parts of Earth's surface.

What is the most common landform on Earth's surface?

An attempt to appreciate the significance of streams and stream valleys in Earth's regional landscape presents a problem of perspective. Viewed from the ground, Earth's stream valleys may appear to be only irregular depressions between rolling hills and plains. Viewed from space, however, stream valleys are seen to dominate most continental landscapes of Earth.

The ubiquitous stream valleys on Earth's surface, and the importance of running water as the major agent of erosion, can best be appreciated by taking a broad, regional view of the continents and their major river systems (Figure 12.1). As the topographic maps in Figure 12.2 show, the surface, throughout broad regions of the continents, is little more than a complex of valleys created by stream erosion. Even in the desert, where it sometimes does not rain for decades, networks of dry stream valleys commonly are major landforms. No other landform on the continents is as abundant and significant. Look again at the space photograph in Figure 2.5. Is any part of the terrain not influenced by stream erosion?

MAJOR CHARACTERISTICS OF RIVER SYSTEMS

A river system consists of a main channel and all of the tributaries that flow into it. It can be divided into three subsystems: (1) a collecting system, (2) a transporting system, and (3) a dispersing system.

Although rivers and the valleys through which they flow are the most familiar of all landforms, it is difficult to define precisely the word *river* because of

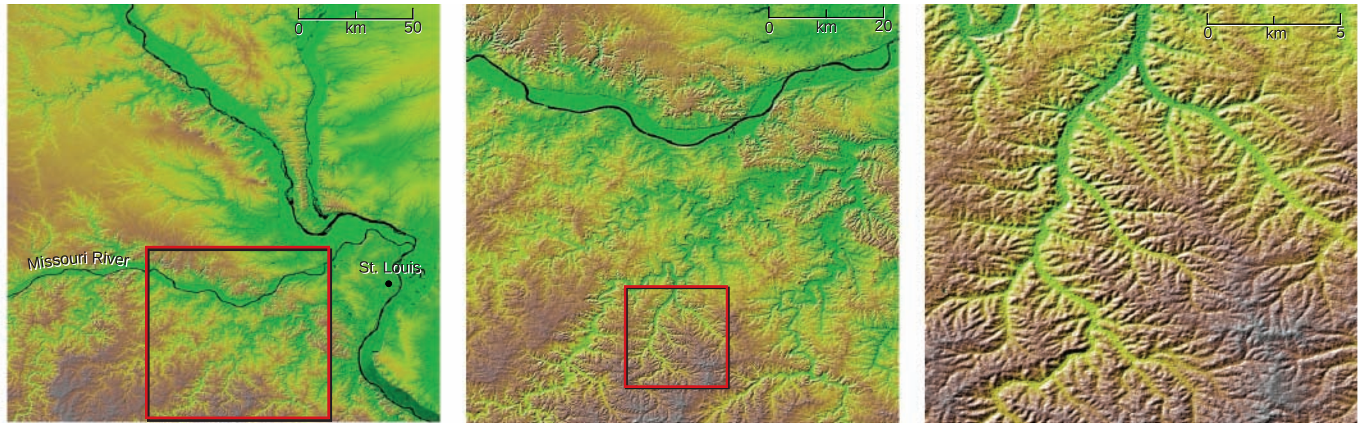
FIGURE 12.1 **Rivers drain most of the continents,** but their distribution and patterns are controlled by climate and plate tectonics. For example, the role of climate is evident in that there are few rivers in the mid-latitude deserts, large rivers in the tropics, and no rivers in the coldest polar areas. Short rivers drain convergent margins (like western North and South America) and long rivers drain the stable platforms (like central North America and Russia) and some shields (like the South American shield).

the great variety of physical characteristics rivers exhibit. There are big rivers, such as the Mississippi, Amazon, and Nile, and there are little rivers, streams, creeks, or brooks. Some rivers in arid regions flow only after a heavy rain and then dry up, whereas rivers in the Arctic are frozen two-thirds of the year. From the viewpoint of geology, it is perhaps most useful to consider a river not as a natural channel through which water flows, but as a system. A **river system,** or **drainage basin,** consists of a main channel and all of the tributaries that flow into it (Figure 12.3). It is bounded by a **divide** (ridge), beyond which water is drained by another system. Within a river system, the surface of the ground slopes toward the network of tributaries, so the drainage system acts as a funneling mechanism for removing surface runoff and weathered rock debris.

A map of a typical river system is shown in Figure 12.3. Three subsystems—a collecting system, a transporting system, and a dispersing system—can be identified. Although the boundaries between the three subsystems are somewhat gradational, the distinguishing characteristics of each subsystem on a regional scale are readily apparent.

The Collecting System

A river's **collecting system** consists of the network of **tributaries** in the headwater region that collect and funnel water and sediment to the main stream. It commonly has a **dendritic** (treelike) **drainage pattern,** with numerous branches that extend upslope toward the divide. Indeed, one of the collecting system's most remarkable characteristics is the intricate network of tributaries, shown in the enlargement in Figure 12.3. This map was made by plotting all visible streams shown on an aerial photograph. It is not, however, the entire system. Each of the smallest tributaries shown on the map has its own system of smaller and smaller tributaries, so the total number becomes astronomical. From the details in Figure 12.2, it is apparent that most of the land's surface is part of some drainage basin.



(A) A map of an area in Missouri shows the regional patterns of the valleys formed by Missouri river system near St. Louis. The area is about 200 km across.

(B) A detailed view of the area reveals an intricate network of streams and valleys within the tributary regions of the large streams.

(C) At even higher resolution, many smaller streams and valleys in the main drainage system are revealed

FIGURE 12.2 **Erosion by running water** is the dominant process in the formation of the landscape and stream valleys are apparent at all scales. *(Courtesy of NASA Shuttle Radar Topography Mission)*

The Transporting System

The **transporting system** is the main trunk stream, which functions as a channel through which water and sediment flow from the collecting area toward the ocean. Although the major process is transportation, this subsystem also collects additional water and sediment. Deposition of sediment commonly occurs where the channel meanders back and forth and when the river overflows its banks during a flood stage. Erosion, deposition, and transportation thus occur, but the main process in this part of a river is the movement of water and sediment.

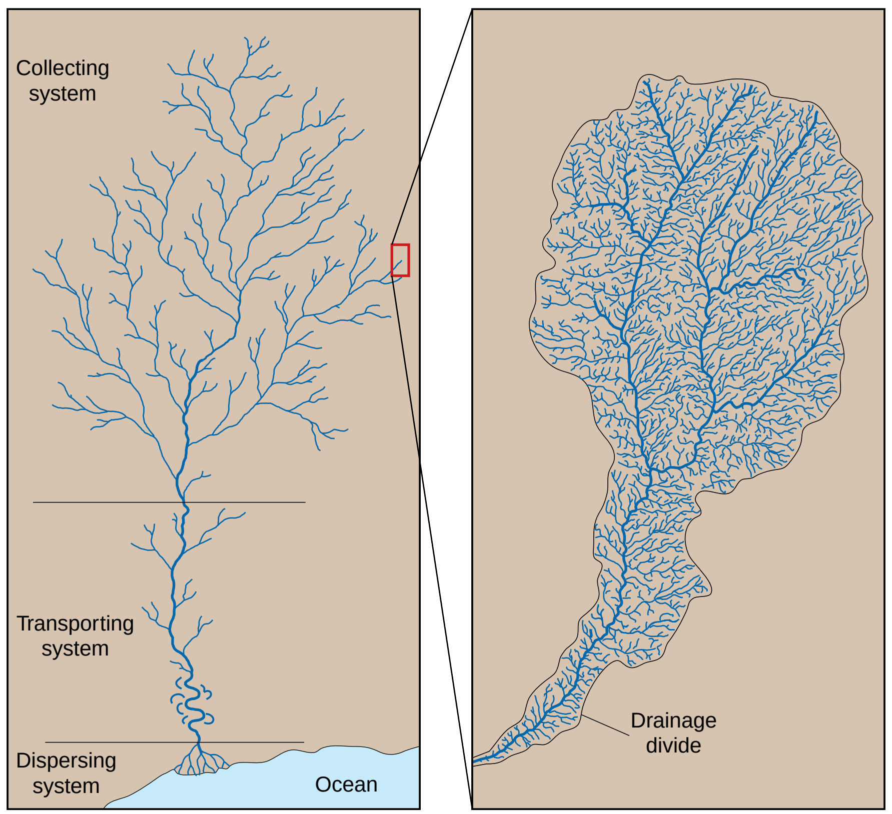


FIGURE 12.3 **The major parts of a river system** are characterized by different geologic processes. The tributaries in the headwaters constitute a subsystem that collects water and sediment and funnels them into a main trunk stream. Erosion is dominant in this headwater area. The main trunk stream is a transporting subsystem. Both erosion and deposition can occur in this area. The lower end of the river is a dispersing subsystem, where most sediment is deposited in a delta or an alluvial fan and water is dispersed into the ocean. Deposition is the dominant process in this part of the river.

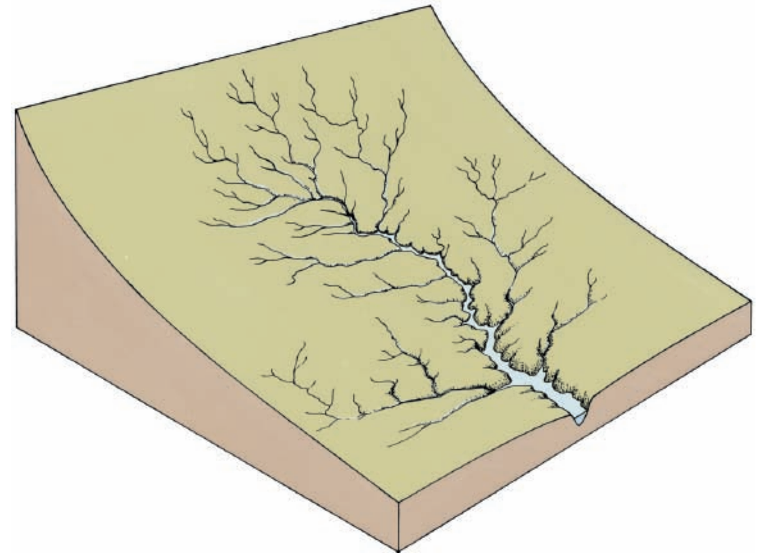


FIGURE 12.4 **The characteristics of a river change systematically** downstream. The gradient decreases downstream, and the channel becomes larger. Other downstream changes include an increase in the volume of water and an increase in the size of the valley through which the stream flows.

The Dispersing System

The **dispersing system** consists of a network of **distributaries** at the mouth of a river, where sediment and water are dispersed into an ocean, a lake, or a dry basin. The major processes are the deposition of the coarse sediment load and the dispersal of fine-grained material and river waters into the basin.

Order in Stream Systems

How do we know that streams erode the valleys through which they flow?

It is apparent from Figures 12.3 and 12.4 that a stream does not occur as a separate, independent entity. Every stream, every river, and every gully and ravine are part of a drainage system, with each tributary intimately related to the stream into which it flows and to the streams that flow into it. Every stream has tributaries, and every tributary has smaller tributaries, extending down to the smallest gully. Studies of drainage systems show that when a stream system develops freely on a homogeneous surface, definite mathematical ratios characterize the relationships between the tributaries and the size and gradient of the stream and of the stream valley. Some of the more important relationships and generalizations are the following:

1. The number of stream segments (tributaries) decreases downstream in a mathematical progression.
2. The length of tributaries becomes progressively greater downstream.
3. The gradient, or slope, of tributaries decreases exponentially downstream.
4. The stream channels become progressively deeper and wider downstream.
5. The size of the valley is proportional to the size of the stream and increases downstream.

These relationships are the basis for the conclusion that streams erode the valleys through which they flow.

If valleys were ready-made by some process other than stream erosion, such as faulting or other earth movements, these relationships would be "infinitely improbable." You can easily confirm the high degree of order in streams by studying Figure 12.2 and Figure 2.5. Does each tributary have a steeper gradient than the stream into which it flows? Does each tributary flow smoothly into a larger stream without an abrupt change in gradient? Are the tributary valleys smaller than the valleys into which they drain?

Geologists have studied stream erosion in great detail over the last 100 years, and they have been able to observe and measure many aspects of stream development and erosion by running water. The origin of valleys by erosion is well established, and running water is clearly the most significant agent of erosion on Earth's surface.

THE DYNAMICS OF STREAM FLOW

Rivers are highly complex systems influenced by several variables. As is the case with so many natural systems, if one variable is changed, it produces a change in the others. The most important variables are (1) discharge, (2) gradient, (3) velocity, (4) sediment load, and (5) base level.

Anyone who has watched the fascinating flow of water in a river realizes that the process is complex. The water moves down the stream channel through the force of gravity, and the velocity of flow increases with the slope, or gradient, of the streambed. In fact, the flow of water in natural streams depends on several factors, the most important of which are discussed below. These variables are intimately related and a change in one causes change in others.

Factors Influencing Stream Flow

Discharge. The amount of water passing a given point during a specific interval of time is called **discharge.** It is usually measured in cubic meters per second. The discharges of most of the world's major drainage systems have been monitored by gauging stations for years. The water for a river system comes from both surface runoff and seepage of groundwater into the stream's channels. Groundwater seepage is important because it can maintain the flow of water throughout the year.

Stream Gradient. Certainly one of the most obvious factors controlling stream flow is the **gradient,** or slope, of the stream channel. The gradient of a stream is steepest in the headwaters and decreases downslope. The **longitudinal profile** (a cross section of a stream from its headwaters to its mouth) is a smooth, concave, upward curve that becomes very flat at the lower end of the stream (Figure 12.4). The gradient usually is expressed in the number of meters the stream descends for each kilometer of flow. The headwater streams that drain the Rocky Mountains can have gradients of more than 50 m/km; the lower reaches of the Mississippi River have a gradient of only 1 or 2 cm/km.

Velocity. Streams flow downhill with velocities that range from a few centimeters per second to as much as 10 meters per second (about 35 km/hr). The velocity of flowing water is proportional to the gradient of the stream channel. Steep gradients produce rapid flow, which commonly occurs in high-mountain streams. Where slopes are very steep, waterfalls and rapids develop, and the velocity approaches that of free fall. Low gradients result in slow, sluggish flow. Where a stream enters a lake or an ocean, its velocity is soon reduced to zero. The velocity of flowing water in a given channel also depends on the water volume. The greater the volume, the faster the flow.

The velocity of flowing water is not uniform throughout a stream channel. It depends on the shape and roughness of the channel and on the stream pattern. The velocity usually is greatest near the center of the channel and above the deepest part, away from the frictional drag of the channel walls and floor (Figure 12.5). As the channel curves, however, the zone of maximum velocity shifts to the outside of the bend, and a zone of minimum velocity forms on the inside of the curve. This flow pattern is an important cause of the lateral erosion of stream channels and of the migration of stream patterns.

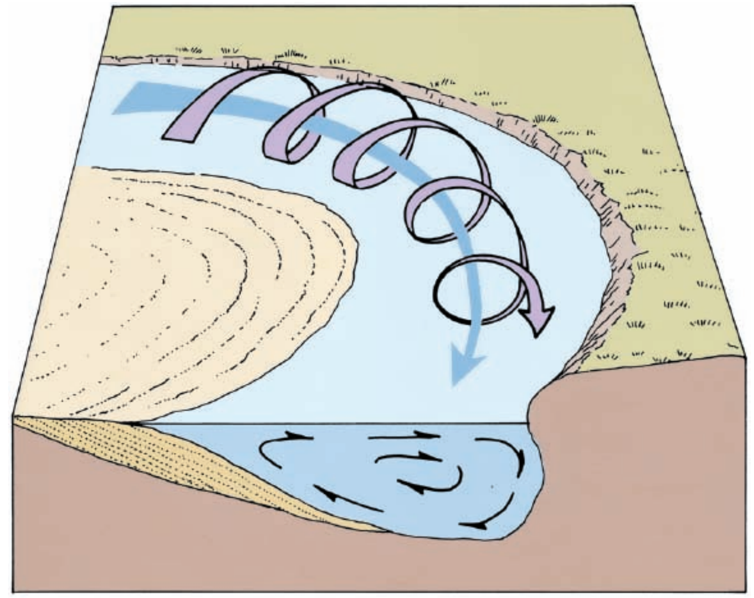


FIGURE 12.5 Flow of water around a meander bend in a river follows a corkscrew pattern. Water on the outside of the bend is forced to flow faster than that on the inside of the curve. This difference in velocity, together with normal frictional drag on the channel walls, produces a corkscrew pattern. As a result, erosion occurs on the outside bank, where velocity is greatest, and deposition occurs on the inside of the bend, where velocity is at a minimum. Erosion on the outside of the meander bend and deposition on the inside cause the stream channel to migrate laterally.

Sediment Load. Running water is the major cause of erosion, not only because it can abrade and erode its channel, but also because of its enormous power to transport loose sediment produced by weathering. Flowing water is a fluid medium by which loose, disaggregated regolith is picked up and transported to the ocean.

Sediment particles can be lifted from a stream bed by hydraulic lift—just as air flowing over a curved wing creates lift that carries an airplane aloft. Some grains bounce off the stream bed when other grains hit them and knock them into the flowing water. In addition, water has a very low viscosity, many times less than that of flowing lava. As a result, its usual flow cannot be described by smooth, simple, streamlines. Instead, it is **turbulent** with many secondary eddies and swirls in addition to the main downstream current. One part of the turbulent flow is vertical and tends to keep small grains suspended in the stream flow.

Once within a stream, sediment is transported in three ways (Figure 12.6):

1. Fine particles are moved in suspension (suspended load).
2. Coarse particles are moved by traction (rolling, sliding, and saltation) along the streambed (bed load).
3. Dissolved material is carried in solution (dissolved load).

The **suspended load** is the most obvious, and generally the largest, fraction of material moved by a river. In most major streams, silt and clay-sized particles remain in suspension most of the time and move downstream at the velocity of the flowing water, to be deposited in an ocean, in a lake, or on a floodplain.

Particles of sediment too large to remain in suspension collect on the stream bottom and form **bed load,** or traction load. These particles move by sliding, rolling, and **saltating** (short leaps). The bed load moves only if there is sufficient velocity

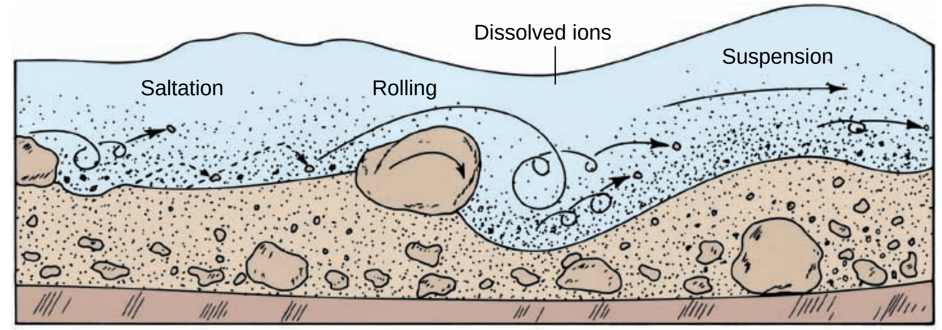


FIGURE 12.6 Movement of the sediment load in a stream is accomplished in a variety of ways. Mud is carried in suspension. Particles that are too large to remain in suspension are moved by sliding, rolling, and saltation. Some ions are dissolved and carried in solution. Increases in discharge, due to heavy rainfall or spring snowmelt, can flush out all of the loose sand and gravel, so the bedrock is eroded by abrasion.

to move the large particles. Part of the bed load can suddenly move in suspension, or part of the suspended load can settle. The bed load can constitute 50% of the total load in some rivers, but it usually ranges from 7% to 10% of the total sediment load. The movement of the bed load is one of the major tools of stream abrasion because as the sand and gravel move, they abrade (wear away) the sides and bottom of the stream channel. In some rivers, the grinding action of the bed load can be heard as large boulders are moved along the river's bottom.

The **dissolved load** is matter transported as chemical ions and is essentially invisible. All streams carry some dissolved material, which is derived principally from the groundwater that emerges from seeps and springs along the riverbanks. The most abundant materials in solution are calcium and bicarbonate ions, but sodium, magnesium, chloride, ferric, and sulfate ions are also common. Various amounts of organic matter are present, and some streams are brown with organic acids derived from the decay of plant material. Flow velocity, which is so important to the transportation of the suspended and traction loads, has little effect on a river's ability to carry dissolved material. Once mineral matter is dissolved, it remains in solution, regardless of velocity, and is precipitated and deposited only if the chemistry of the water changes. Chemical analysis shows that most rivers carry a dissolved load of less than a thousand parts per million. Although these amounts of dissolved material seem small, they are far from trivial. Sampling shows that 5% to 50% of all the material carried to the ocean is in solution. For example, in the Mississippi River the dissolved load is about 30% of the total sediment load.

Velocity is an important control on a stream's ability to erode, transport, and deposit sediment. The **capacity** of a stream is the amount or weight of sediment it carries. Stream capacity increases to a third or fourth power of flow velocity; that is, if the velocity is doubled, the stream can move from 8 to 16 times as much sediment. Another measure of sediment load is its **competence**—the size of the largest particle the stream is able to carry. Competence also increases with velocity.

The results of experimental studies show that a minimum or **threshold velocity** is required to move grains of a certain size (Figure 12.7). The graph shows that at low velocities only small grains can be transported. Higher velocities will generally move larger particles. On the other hand, where the stream's velocity is low, a significant part of the sediment load is deposited along the channel or on the floodplain. Sediment may also be deposited where the velocity is reduced, such as when a river enters a lake or the ocean.

Base Level. The **base level** of a stream is the lowest level to which the stream can erode its channel. The base level is, in effect, the elevation of the stream's mouth, where the stream enters an ocean, a lake, or another stream. A tributary cannot erode lower than the level of the stream into which it flows. Similarly, a lake controls the level of erosion for the entire course of the river that drains into it. The levels of tributary junctions and lakes are temporary base levels: Lakes can be filled with sediment or drained, and streams can then be established across

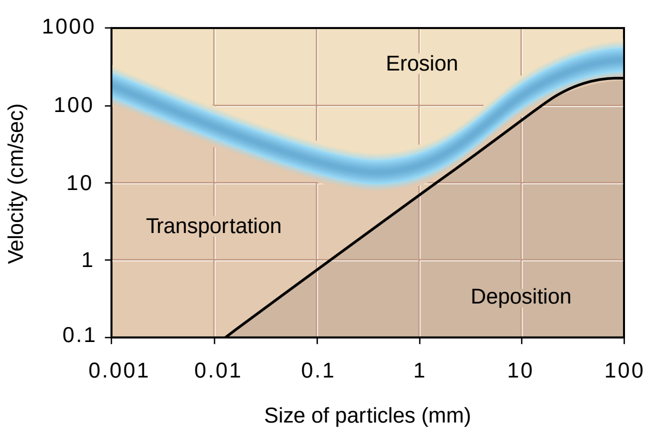


FIGURE 12.7 The threshold velocity for sediment transport shows the minimum velocities at which a stream can pick up and move a particle of a given size. This threshold velocity is represented by a zone, not by a line, because of variations resulting from stream depth, particle shape, and density. The lower curve indicates the velocity at which a particle of a given size settles out and is deposited. Note that fine particles stay in suspension at velocities much lower than those required to lift them from the surface of the streambed.

the former lake bed. For all practical purposes, the ultimate base level is sea level because the energy of a river is quickly reduced to zero as it enters the ocean. Therefore, base level is an extremely important control on the extent of stream erosion, and a drop in base level commonly creates the basal unconformity of a sedimentary sequence.

EQUILIBRIUM GRADIENTS IN RIVER SYSTEMS

A river system functions as a unified whole: Any change in one part of the system affects the other parts. The major factors that determine stream flow constantly change toward a balance, or equilibrium, so that the gradient of the stream is adjusted to accommodate the volume of the water available, the channel's characteristics, and the velocity necessary to transport the sediment load.

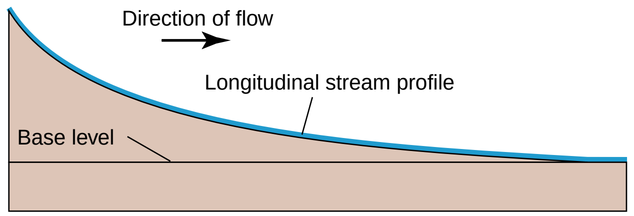
We have repeatedly emphasized the fact that any one part of a stream does not occur as a separate, independent entity. One of the most important characteristics of a river system is that it functions as a unified whole: Any change in one part of the system affects the other parts. The major factors that determine stream flow (discharge, velocity, channel shape, gradient, base level, and load) constantly change. A change in any of these factors causes compensating adjustments in another factor to restore balance or equilibrium in the entire drainage system. A river is in equilibrium if its channel form and gradient are balanced so that neither erosion nor deposition occurs. Rivers are constantly adjusting to approach this ideal condition. This adjustment is important in understanding the natural evolution of the landscape. It also has practical considerations: If we are going to continually manipulate rivers to suit our needs, we should know how river systems respond to changes.

What is the profile of equilibrium in a river system?

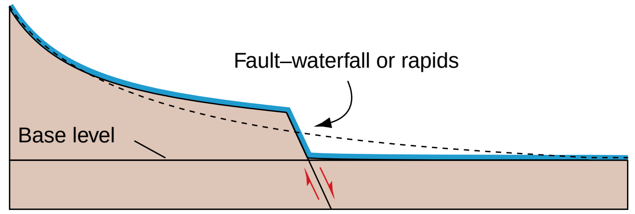
The concept of equilibrium in a river system can be appreciated by considering a hypothetical stream in which equilibrium has been established. In Figure 12.8A, the variables in the stream system are in balance, so neither erosion nor deposition occur along the stream's profile. There is just enough water to transport the available sediment down the existing slope. Such a stream is in equilibrium and is known as a **graded stream.** In Figure 12.8B, the stream's profile is displaced by a fault that creates a waterfall. The increased gradient across the fault greatly increases the stream's velocity at that point, so rapid erosion occurs, and the waterfall (or the rapid) begins to migrate upstream. The eroded sediment added to the stream segment on the dropped fault block is more than the stream can transport because the system was already in equilibrium before faulting occurred. The river therefore deposits part of its load at that point, thus building up the channel gradient (the yellow areas in Figure 12.8C–D) until a new profile of equilibrium is established.

An example of the adjustments just described occurred in Cabin Creek, a small tributary of the Madison River, north of the Hebgen Dam in Montana. In 1959, during the Hebgen Lake earthquake, a 3-m fault scarp formed across the creek. By June 1960, erosion by Cabin Creek had erased the waterfall at the cliff formed by the fault, and only a small rapid was left. By 1965, the rapid was completely removed, and equilibrium was reestablished.

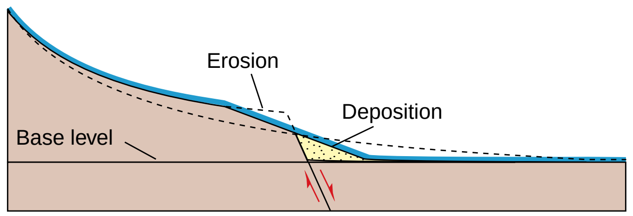
Equilibrium in a river system is also illustrated by the results of dam construction. In the reservoir behind a dam, the gradient is reduced to zero. Hence, where the stream enters the reservoir, its sediment load is deposited as a delta and as layers of silt and mud over the reservoir floor (Figure 12.9). Because most sediment is trapped in the reservoir, the water released downstream has practically no sediment load. The clear water in the river downstream of the dam is therefore capable of much more erosion than the previous river, which carried a sediment



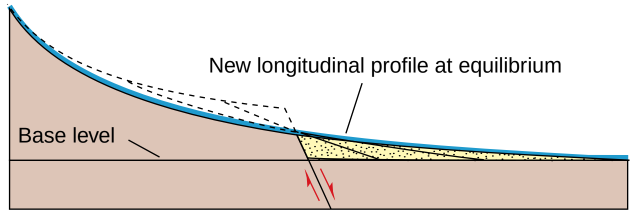
(A) Initially, when the stream profile is at equilibrium, the velocity, load, gradient, and volume of water are in balance. Neither erosion nor deposition occurs.



(B) Faulting disrupts equilibrium by decreasing the gradient downstream and increasing the gradient at the fault line.



(C) Erosion proceeds upstream from the fault, and deposition occurs downstream and a new stream profile starts to develop.



(D) Erosion and deposition eventually develop a new stream profile at which the velocity, load, gradient, and volume of water will be in balance so that neither erosion nor deposition occurs.

FIGURE 12.8 **Adjustment of a stream to reestablish equilibrium** is shown by profile changes after disruption by faulting. Erosion and deposition develop a new stream profile at which the velocity, load, gradient, and volume of water will be in balance so that neither erosion nor deposition occurs.

load adjusted to its gradient. As a result, extensive scour and erosion commonly result downstream from a new dam.

The Nile and River Equilibrium

The Aswan High Dam on the Nile River in Egypt provides a good example of the many consequences of modifying a river system that has approached equilibrium. For centuries, the Nile River has been the main source of life in Egypt (Figure 2.2). The Nile's principal headwaters are located in the high plateaus of Ethiopia. Once a year, for approximately a month, the Nile used to rise to flood stage and cover much of the fertile farmland in the Nile Delta area. The Aswan High Dam was completed in the summer of 1970. It was intended to provide Egypt with water

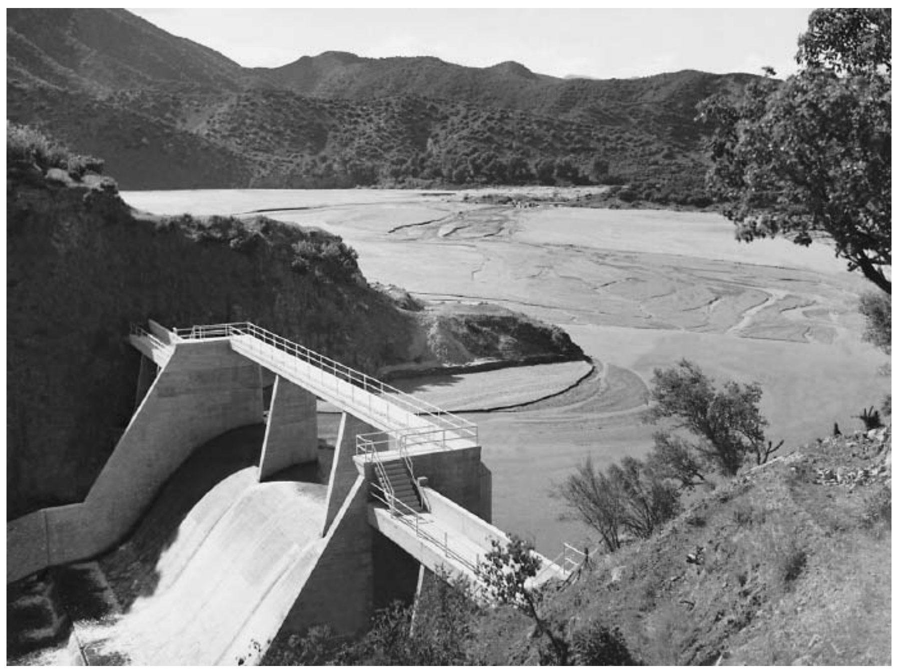


FIGURE 12.9 **The volume of sediment transported** by a stream is illustrated by the Mono Reservoir in California, which has been completely filled with sand and mud. *(Courtesy of U.S.D.A. Forest Service)*

to irrigate 1 million acres of arid land and to generate 10 billion kilowatts of power, which, in turn, was to double the national income and permit industrialization. The dam, however, destroyed the Nile's equilibrium, and many unforeseen adjustments in the river resulted (Figure 12.10). This is what happened.

The Nile is not only the source of water for the delta; it is also the source of sediment. When the dam was finished and began to trap sediment in a reservoir (Lake Nasser), the physical and biological balance in the delta area was destroyed. Without the annual "gift of the Nile," the delta coastline is now exposed to the full force of marine currents, and wave erosion is eating away at the delta front. Some parts of the delta are receding several meters a year.

The sediment previously carried by the Nile was an important link in the aquatic food chain, nourishing marine life in front of the delta. The recent lack of Nile sediment has reduced plankton and organic carbon to a third of the former levels. This change either killed off or drove away sardines, mackerel, clams, and crustaceans. The annual harvest of 16,000 metric tons of sardines and a fifth of the fish catch have been lost.

The sediment of the Nile also naturally fertilized the floodplain. Without this annual addition of soil nutrients, Egypt's 1 million cultivated acres need artificial fertilizer.

The water discharged from the reservoir is clear, free of most of its sediment load. Without its load, the discharged water flows swiftly downstream and is vigorously eroding the channel bank. This scouring process has already destroyed three old barrier dams and more than 500 bridges built since 1953. Ten new barrier dams must be built between Aswan and the ocean at a cost equal to one-fourth the cost of the Aswan Dam itself.

The annual Nile flood was also important to the area's ecology because it washed away salts that accumulated in the arid soil. Soil salinity has already increased, not only in the delta, but throughout the middle and upper Nile areas. Unless corrective measures are taken (at a cost of more than U.S. $1 billion), millions of acres will become unproductive within a decade. Also, the control of the river has resulted in stagnation of the channels and overgrowth of vegetation (Figure 12.10).

The change in the river system has permitted double cropping, but this eliminated periods of dryness. The dry seasons previously helped limit the population of bilharzia, a blood parasite carried by snails that infects the intestinal and urinary

FIGURE 12.10 **The Nile River** has been dramatically affected by the construction of the Aswan High Dam. Without the annual flood, the river stagnates and is commonly overgrown with vegetation. *(Courtesy of Yann Arthus-Bertrand/Peter Arnold, Inc.)*

(A) Surface runoff vs. infiltration under natural conditions. From 80% to 100% of the surface water filters into the subsurface, and from 0% to 20% flows through the drainage system. Runoff is distributed over a long period with a small peak flow.

(B) Surface runoff vs. infiltration in urban areas. From 0% to 10% filters into the subsurface, and from 90% to 100% moves as surface runoff. Peak flow is very high and occurs in a short period of time.

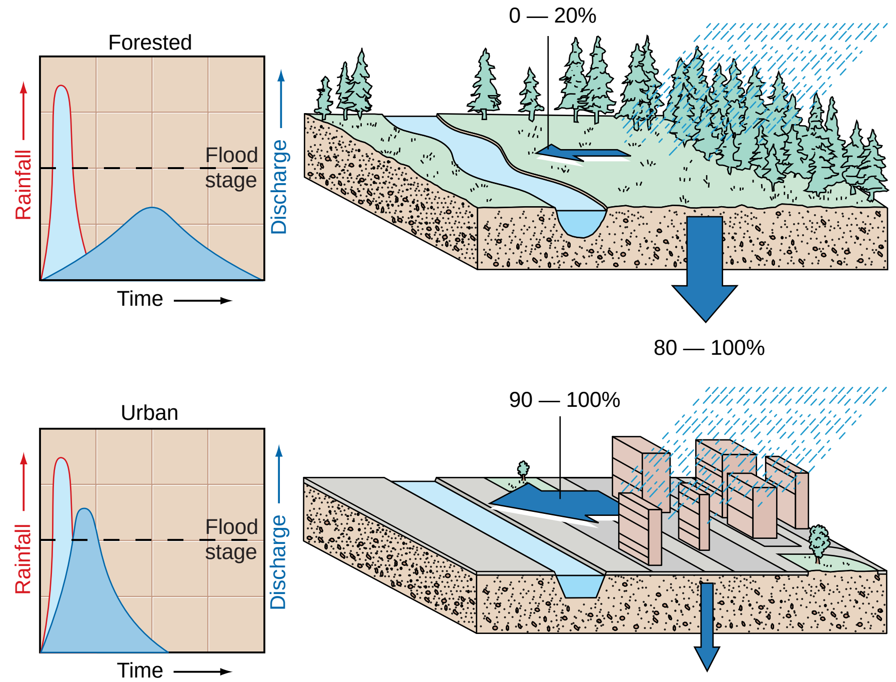


FIGURE 12.11 **Urbanization** has affected the amount and rate of runoff.

tracts of humans. One out of every two Egyptians now has the infection, and it causes a tenth of the deaths in the country.

What changes occur when a dam is built on a river?

Problems have also occurred in the lake behind the dam. The lake was to have reached a maximum level in 1970, but it might actually take 200 years to fill. More than 15 million cubic meters of water annually seep underground into the porous Nubian Sandstone, which lines 480 km of the lake's western bank. The sandstone is capable of absorbing an almost unlimited quantity of water. Moreover, the lake is in one of the hottest and driest places on Earth, and the rate of evaporation is staggering. A high rate was expected, but additional losses from transpiration by plants growing along the lakeshore and increased evaporation caused by high winds have brought the total loss of water from the lake to nearly double the expected rate. This loss equals half the total amount of water that once was "wasted," flowing unused to the ocean.

Effects of Urbanization on River Equilibrium

Another way that equilibrium in river systems has been disrupted is through urbanization. The construction of cities may at first seem unrelated to the modification of river systems, but a city significantly changes the surface runoff, and the resulting changes in river dynamics are becoming serious and costly. Water that falls to Earth as precipitation usually follows several paths in the hydrologic system. In general, from 54% to 97% returns to the air directly by evaporation and transpiration; the remaining water collects in stream systems as surface runoff or infiltrates the ground and moves slowly through the subsurface toward the ocean. Under natural conditions, 80% to 100% of the surface runoff infiltrates into the subsurface. Urbanization disrupts each of these paths in the normal hydrologic system. It changes the nature of the terrain and consequently affects the rates and percentages of runoff and infiltration. Roads, sidewalks, and roofs of buildings render a large percentage of the surface impervious to infiltration. Not only does the volume of surface runoff increase, but runoff is much faster because water is channeled through gutters, storm drains, and sewers. As a result, flooding increases in intensity and frequency (Figure 12.11).

PROCESSES OF STREAM EROSION

River systems erode the landscape by three main processes: (1) removal of regolith, (2) downcutting of the stream channel by abrasion, and (3) headward erosion.

Erosion of the land is one of the major effects of the hydrologic system. It has occurred on all continents throughout all of geologic time and will continue as long as the system operates and land is exposed above sea level (Figure 12.12). Evidence of erosion is ubiquitous and varied. We see it in the development of gullies on farmlands and in the cutting of great canyons. We see it in the thick layers of sedimentary rocks that cover large parts of the continents and bear witness to erosion and deposition in past ages. But exactly how does a river system erode the land? How can a relatively small stream such as the Colorado River erode the Grand Canyon, which is more than 2 km deep and 25 km wide? What processes are involved in erosion? How do river systems evolve? Answers to these basic questions have eluded scientists until recently, and even today some details remain controversial. However, we now know that erosion by running water and the evolution of a river system are accomplished by three basic processes: (1) removal of regolith, (2) downcutting of the stream channel by abrasion, and (3) headward erosion.

Removal of Regolith

One of the most important processes of erosion is the removal and transport of rock debris (regolith) produced by weathering. The process is simple but important. Loose rock debris created by weathering is washed downslope into the

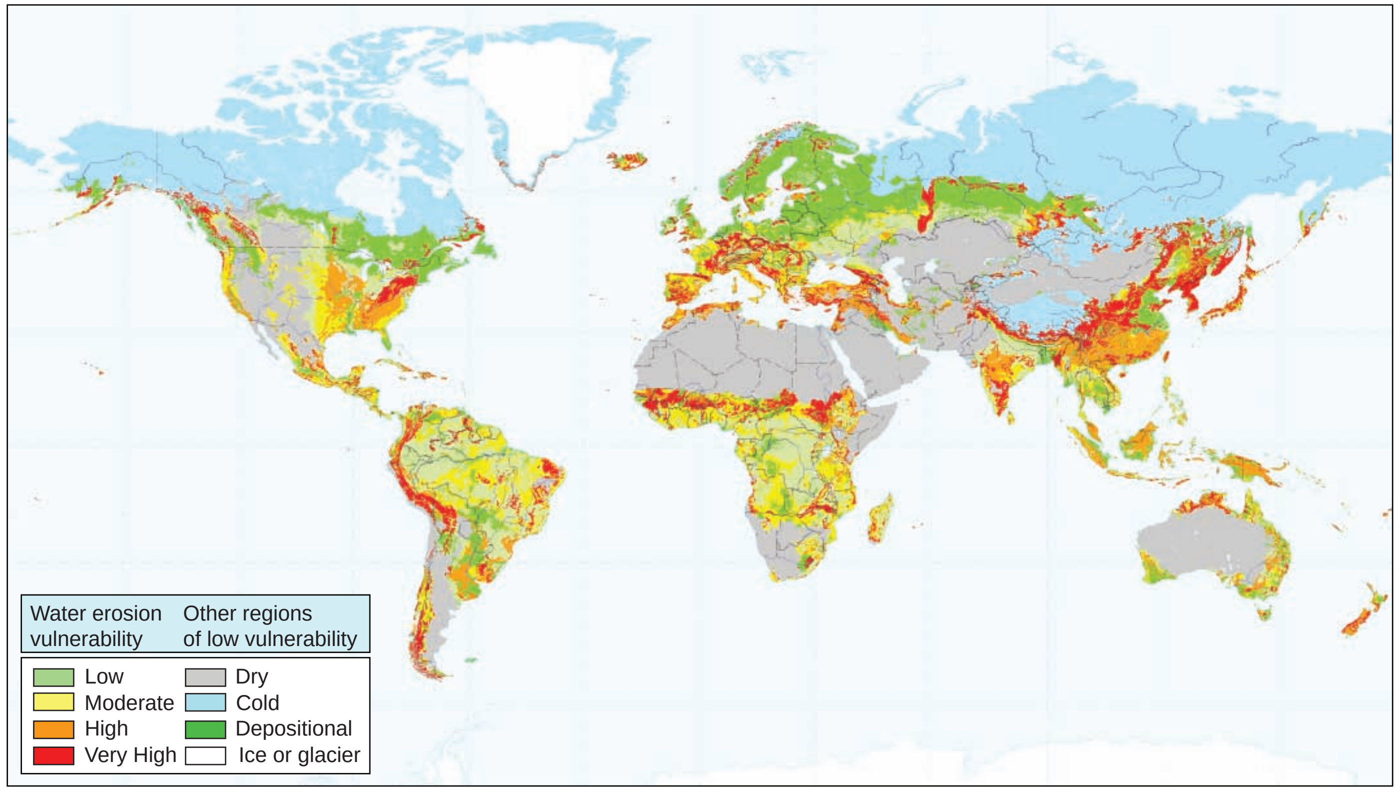


FIGURE 12.12 **Water erosion vulnerability** varies across the globe in a systematic way and is closely related to climate and topography. Two large regions are climatically controlled: The Arctic regions (blue) which have been glaciated and/or influenced by permafrost, and the great desert regions (gray) which have low vulnerability simply because there isn't enough water for significant stream erosion. In much of the desert regions deposition by wind and intermittent streams dominates. Areas of very high vulnerability are mountainous regions with high rainfall.

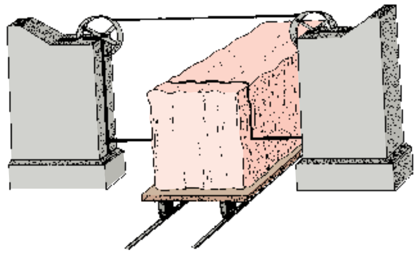


FIGURE 12.13 Sketch of a wire saw commonly used in quarry operations. The wire is pulled across the rock, dragging abrasives as it moves. When the rock is raised (or the wire is lowered), the abrasives, dragged across the rock by the wire, slice through the block.

drainage system and is transported as sediment load in streams and rivers. In addition, soluble material is carried in solution. The net result is that the blanket of regolith created by weathering is continually being removed and transported to the sea by stream action. As it is removed, however, it is also continually being regenerated by the weathering of the fresh bedrock below. Measurements of the amount of sediment carried by rivers suggest that about 6 cm/1000 yr are removed from the continents.

Downcutting of Stream Channels

Downcutting is a fundamental process of erosion in all stream channels, whether small hillsides, gullies, or great canyons of major rivers. The process is accomplished by the **abrasion** of the channel floor by sand and gravel as they are swept downstream by the flowing water. It is similar in many respects to the action of a wire saw used in quarries to cut and shape large blocks of stone (Figure 12.13). An abrasive such as garnet, corundum, or quartz, dragged across a rock by a wire, can cut through a stone block with remarkable speed.

Some dramatic examples of the power of streams to cut downward are the steep, nearly vertical gorges in many canyons in the southwestern United States (Figure 12.14). Although the bed load of sand and gravel on the channel floor is stationary much of the time, during spring runoff and periodic flash floods, it moves with the flowing water. This material is an effective abrasion tool and can cut the stream channel to a profile of equilibrium in a short time. The power of downcutting is also expressed by the entrenchment of rivers to form deep canyons (Figure 12.15).

An effective and interesting type of abrasion of the channel floor is the drilling action of pebbles and cobbles trapped in a depression and swirled around by currents. The rotational movement of the sand, gravel, and boulders acts like a drill and cuts deep holes known as **potholes.** As the pebbles and cobbles are worn away, new ones take their place and continue to drill into the bedrock of the stream channel. Some potholes are several meters in diameter and more than 5 m in depth (Figure 12.16).

As the pebbles and cobbles are carried by flowing water, they themselves are worn down by striking one another and the channel bottom. Their corners and edges are chipped off, and the particles become smaller, smoother, and more rounded. Large boulders that have fallen into a stream and are transported only during a flood are thus slowly broken and worn down to smaller fragments. Ultimately, they are washed away as grains of sand.

FIGURE 12.14 The tools of erosion are sand and gravel. Transported by a river, they act as powerful abrasives, cutting through the bedrock as they are moved by flowing water. The abrasive action of sand and gravel cut this vertical gorge through resistant limestone in the Grand Canyon, Arizona.

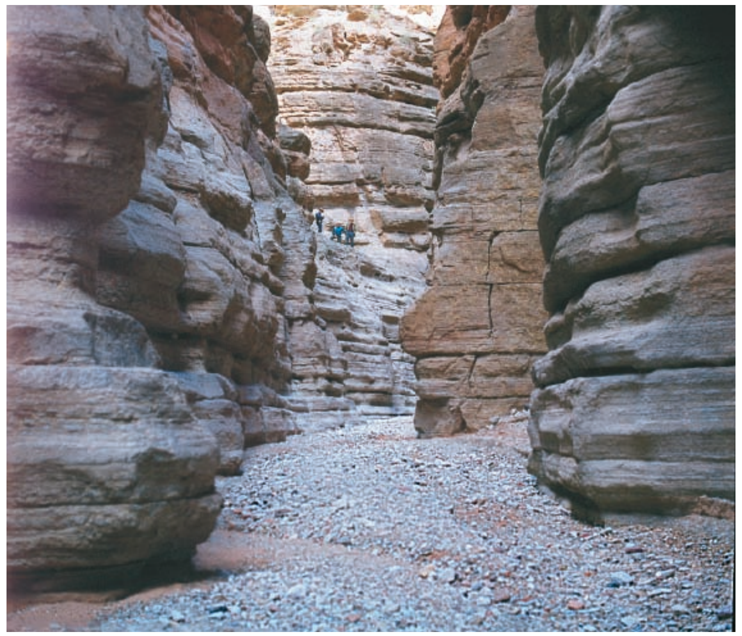


FIGURE 12.15 Entrenched meanders of the Colorado River resulted from downcutting of the river channel more than 300 m.

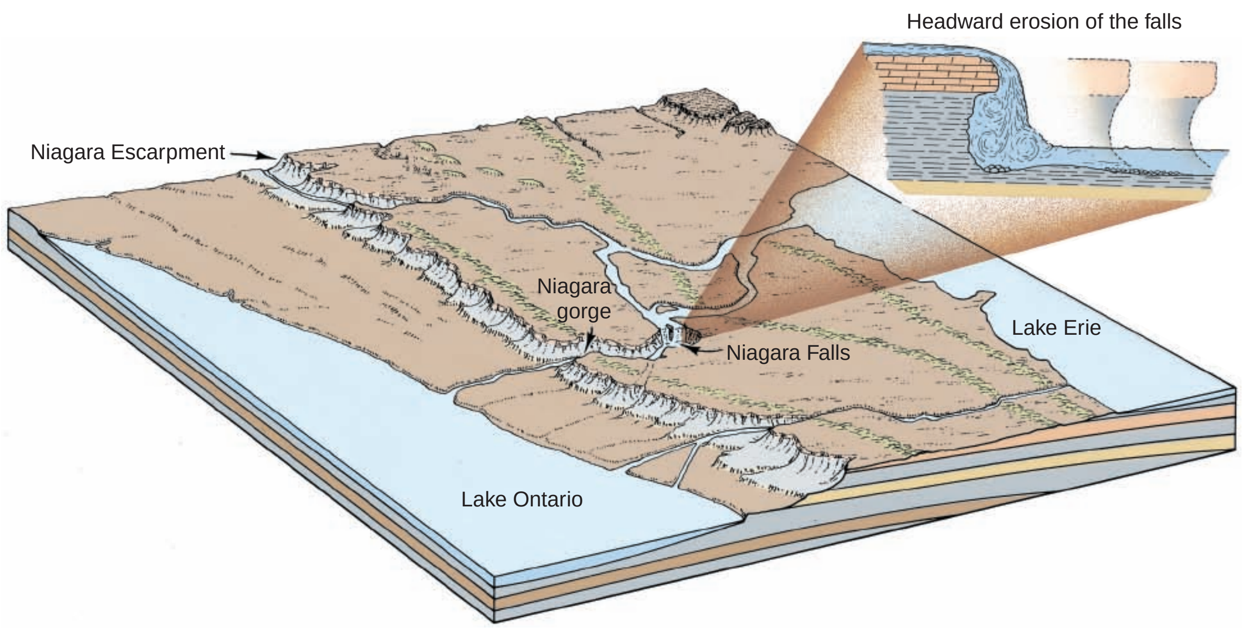
Another important factor in the downcutting of a stream channel is the upstream migration of waterfalls and rapids. Here again, the process is simple but important. It can be appreciated by considering the erosion of Niagara Falls (Figure 12.17). The increased velocity of the falling water sets up strong turbulence at the base of the falls, causing rapid erosion of the underlying weak, nonresistant rock layers. The cliff is gradually undermined, and the falls retreat upstream. During the last 12,000 years, Niagara Falls has migrated headward more than 11.5 km.

Slope retreat also plays an important role in shaping stream valleys. Mass movement and the erosion of small tributaries reduce steep valley walls to gentle slopes. In the process, much new sediment enters the river system.

Headward Erosion

In the process of stream erosion and valley evolution, streams have a universal tendency to erode headward, or upslope, and to increase the lengths of their valleys until they reach the divide. **Headward erosion** can be analyzed by referring to Figure 12.18. The reason erosion is more vigorous at the head of a valley than on its sides is apparent from the relationships between the valley and the regional slope. Above the head of a valley, water flows down the regional slope as sheets (sheet flow), but the water starts to converge to a point where a definite stream channel begins. As the water is concentrated into a channel, its velocity and erosive power increase far beyond those of the slower-moving sheet of water on the surrounding ungullied surface. The additional volume and velocity of the channel water erode the head of the valley much faster than sheet flow erodes ungullied

FIGURE 12.16 Potholes are eroded in a streambed by sand, pebbles, and cobbles whirled around by eddies. These potholes on the floor of the Blyde River Canyon in South Africa are about 3 m across.



(A) The Niagara River originated as the last glacier receded from the area and water flowed from Lake Erie to Lake Ontario over the Niagara Escarpment. Erosion causes the waterfalls to migrate upstream at an average rate of about 1 m/yr.

(B) Niagara Falls presents a spectacular scene as large volumes of water fall vertically over the cliffs of limestone. The falls are 70 m high and have migrated headward more than 11.5 km in the last 12,300 years. *(© Joseph Sohn: Visions of America/CORBIS)*

FIGURE 12.17 **Retreat of Niagara Falls upstream** occurs as hydraulic action undercuts the weak shale below the limestone.

slopes or the valley walls. In addition, groundwater moves toward the valley, so the head of the valley is a favorable location for the development of springs and seeps. These, in turn, help to undercut overlying resistant rock and cause headward erosion to occur much faster than retreat of the valley walls. The head of the valley is thus extended upslope.

Stream Piracy. With the universal tendency for headward erosion, the tributaries of one stream can extend upslope and intersect the middle course of another stream, thus diverting the headwater of one stream to the other. This process, known as **stream piracy,** is illustrated in Figure 12.19. Stream piracy is most likely to occur if headward erosion of one stream is favored by a steeper gradient or by a course in more easily eroded rocks. Some of the most spectacular examples occur in the folded Appalachian Mountains, where nonresistant shale and limestone are interbedded with resistant sandstone formations. The process of stream capture and the evolution of the region's drainage system are shown in the series of diagrams in Figure 12.20. The original streams flowed in a dendritic pattern (a branching, treelike pattern) on horizontal sedimentary layers that once covered the folds. As uplift occurred, erosion removed the horizontal sedimentary rocks, and the dendritic drainage pattern became superposed, or placed on, the folded rock beneath. The **superposed stream** thus cuts across weak and resistant rocks alike. As the major stream cuts a valley across the folded rocks, new tributaries rapidly erode headward along the nonresistant formations. By headward erosion, these new streams progressively capture the superposed tributaries and change the dendritic drainage pattern to a **trellis drainage pattern** (a pattern in which the tributaries join the main stream at right angles).

Extensive stream piracy and development of a trellis drainage pattern can be seen almost any place where folded rocks are exposed at the surface. In the folded Appalachian Mountains, the major streams that flow to the Atlantic (such as the Susquehanna and the Potomac) are all superposed across the folded strata. Their tributaries, however, flow along the nonresistant rocks parallel to the geologic structure and have captured many superposed tributary streams.

Another example of stream piracy is the Pecos River in New Mexico. By extending itself headward to the north along the weak shale and limestone, which crop out in a north–south zone parallel to the Rocky Mountain front, it has captured a series of eastward-flowing streams that once extended from the Rockies across the Great Plains. The original eastward drainage (shown in Figure 12.21A) resulted from the uplift of the Rocky Mountains. Now the headwaters of most of the original streams have been captured by the Pecos River. Water that once would have flowed across the Llano Estacado (the High Plains of Texas) now flows down the Pecos valley (Figure 12.21B).

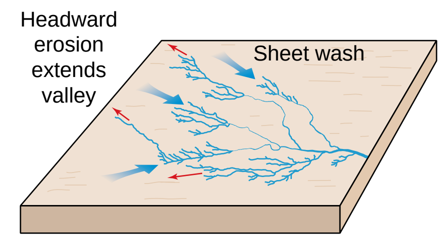


FIGURE 12.18 **Headward erosion** is constantly extending the drainage upslope so that the network of tributaries is enlarged and consumes the flat, undissected upland. Water flows as a sheet down the undissected regional slope. As it converges toward the head of a tributary valley, its velocity and volume are greatly increased, so its ability to erode also increases. The tributary valley is thus eroded headward, up the regional slope.

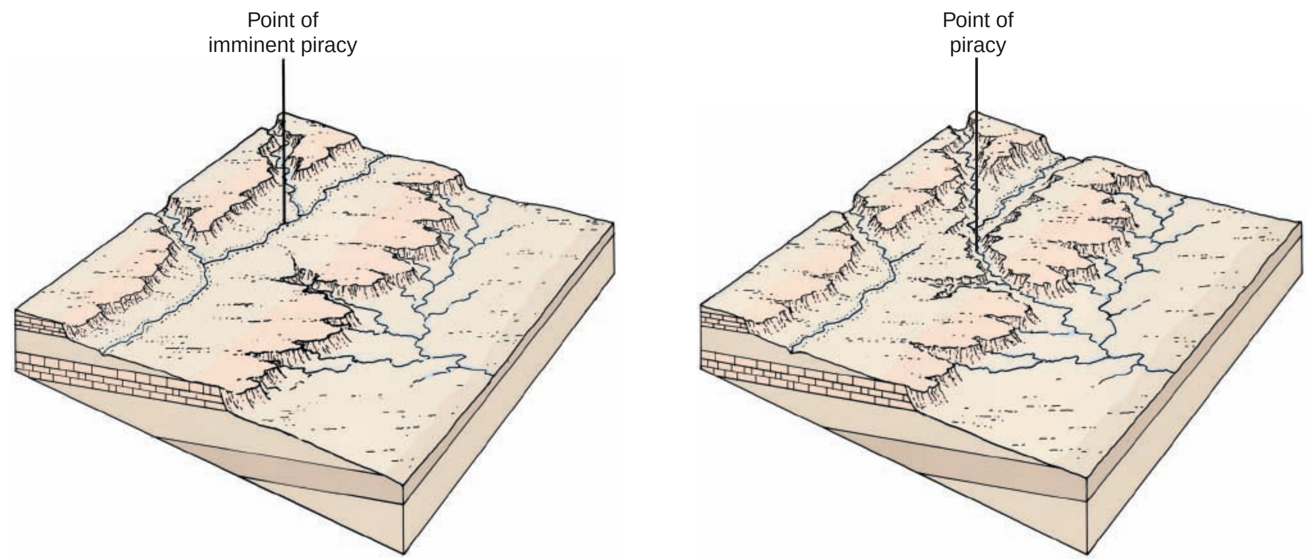
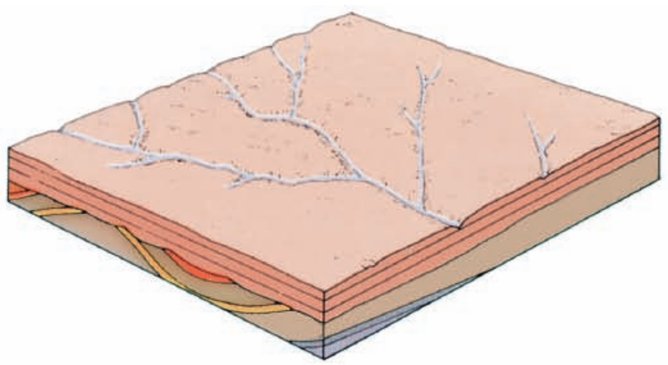
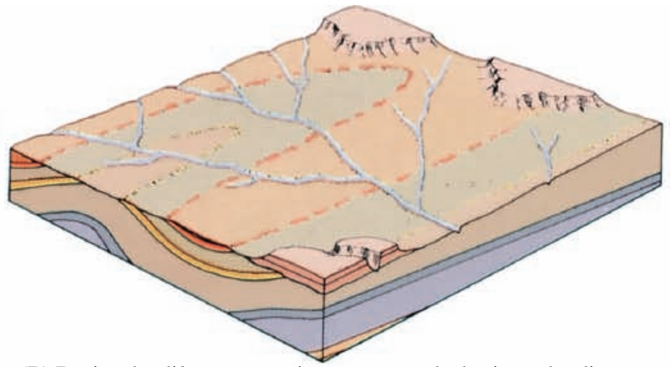


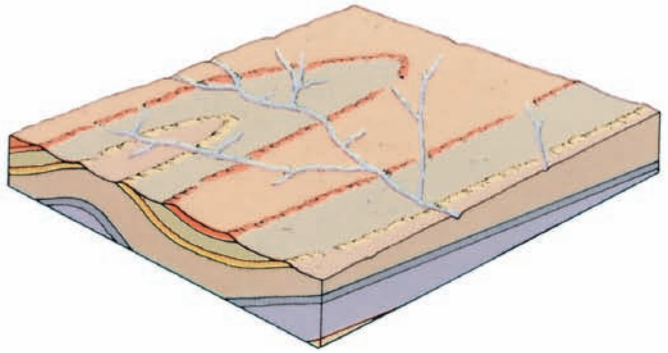
FIGURE 12.19 **Stream piracy** occurs where a tributary with a high gradient rapidly erodes headward and captures a tributary of another stream.



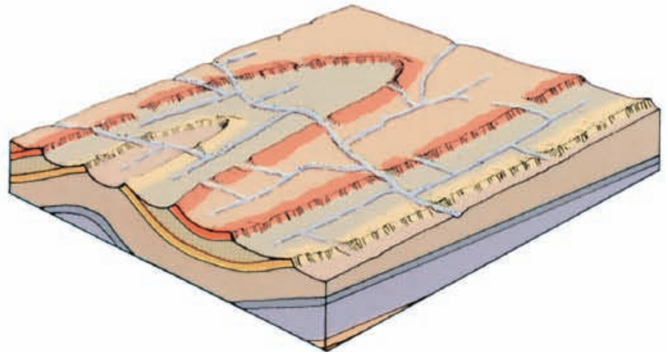
(A) Initially, a dendritic pattern formed on horizontal sedimentary rocks, which cover the older, eroded folds.



(B) Regional uplift causes erosion to remove the horizontal sediments, thereby exposing the older, folded rocks at the surface. The dendritic drainage pattern is then superposed, or placed on, the folded rocks.

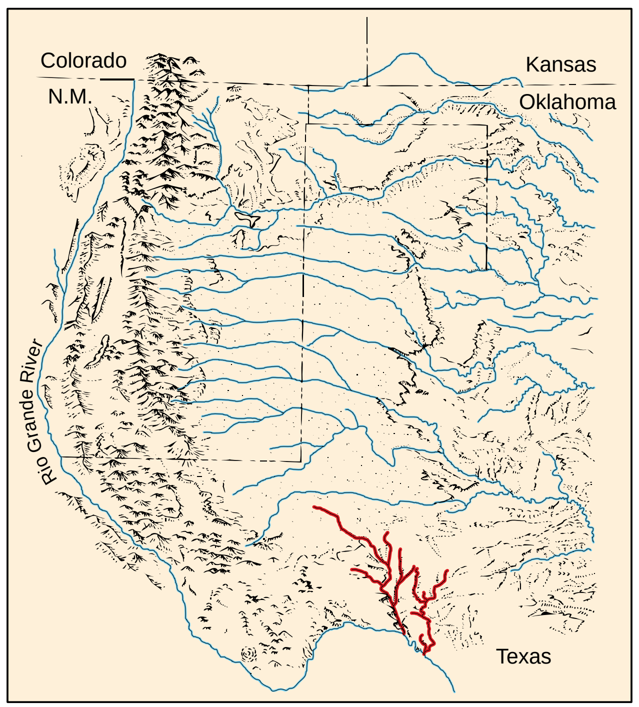


(C) Main streams cut across both resistant and nonresistant rock by channel abrasion.



(D) Rapid headward erosion along exposures of weak rocks results in stream capture and modification of the dendritic pattern to a trellis pattern.

FIGURE 12.20 **A dendritic drainage pattern superposed** on a series of folded rocks evolves into a trellis pattern as headward erosion proceeds along nonresistant rock formations.



(A) Prior to the development of the Pecos valley, drainage is believed to have been eastward from the Rocky Mountains across the Great Plains.

(B) Headward erosion of the Pecos River northward along the nonresistant rocks of the Pecos plains captured the headwaters of the eastward-flowing streams.

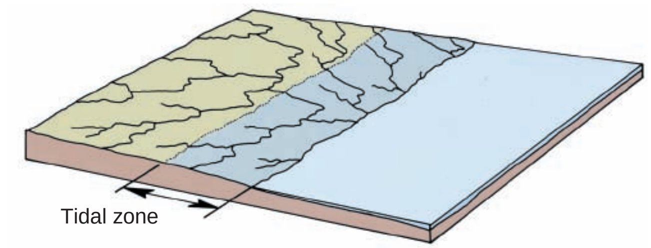
FIGURE 12.21 **The Pecos River** evolved as headward erosion extended the drainage network northward and captured the eastward-flowing streams.

Extension of Drainage Systems Downslope

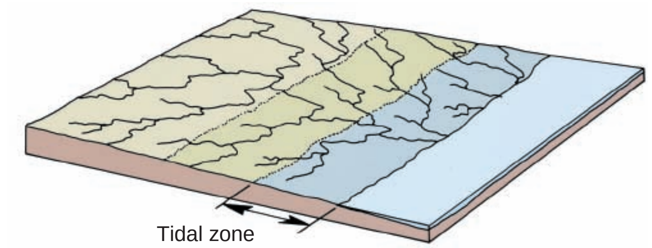
In addition to downcutting and headward erosion, a drainage system can grow in length simply by extending its course downslope as sea level falls or as the landmass rises. This process is probably fundamental in determining the original course of many major streams, especially in the interior lowlands, where the oceans once covered much of the continents and then slowly withdrew. During a regression of the sea, drainage systems were extended down the newly exposed slopes. Later, they were modified by headward erosion and stream piracy.

River Erosion

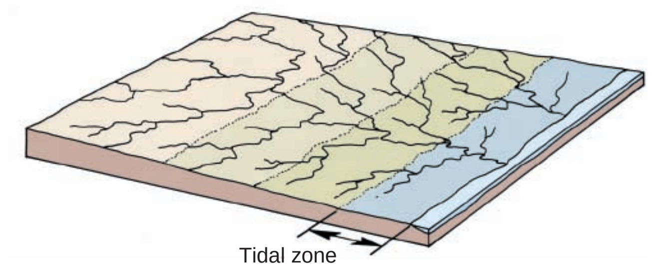
Tidal channels (major channels formed by tidal currents extending from offshore well into the tidal flat) along coastal plains are examples of the beginning of a new segment of a drainage system as a result of a fall in sea level. The pattern of land and tidal drainage is characteristically dendritic because the material on which this drainage is established consists of recently deposited horizontal sediments. If the slope is pronounced, however, the tributaries, as well as the major streams, flow parallel for a long distance. If sea level were to drop, the streams would continue to flow downslope, following the courses established by tidal channels, as is shown in Figure 12.22. Major streams would extend their drainage patterns over the deltas that they deposited. Most of the streams in the Gulf and Atlantic coastal plains originated in this way. If sea level is falling, the youngest parts of a river are therefore near the shoreline and upslope, where headward erosion develops new channels.



(A) In the original position of the shore, tidal channels develop between high tide and low tide.



(B) As the sea level falls and the shoreline recedes, tidal channels become part of the permanent drainage system.



(C) With each successive retreat of the shoreline, new tidal channels develop and drainage is extended farther downslope. A dendritic drainage pattern typically is produced on the homogeneous tidal-flat material.

FIGURE 12.22 **Extension of a drainage system downslope** occurs as a shoreline recedes. This downslope extension commonly results in a dendritic pattern.

The Grand Canyon: A Model of Stream Erosion

Because the evolution of a drainage system may require tens of millions of years, we can study the origin of stream valleys only indirectly. One approach is to study the interaction of downcutting and slope retreat by means of a computer model of the Colorado River's erosion of the rock sequence in the Grand Canyon area. Variables of a drainage system that affect various rock formations, such as rates of downcutting and slope retreat, were analyzed. This study produced a series of hundreds of computer-calculated profiles of the Grand Canyon, showing changes that have occurred between the time the Colorado River began cutting through the Colorado Plateau and the present.

Although this model cannot be verified directly, you can get a glimpse of the stages of canyon development by studying the canyon longitudinally (Figure 12.23). Upstream, near Lees Ferry, the river is just beginning to cut through the Kaibab Limestone. Here, uplift has been minimal, and the entire sequence of strata exposed farther downstream in the Grand Canyon is below the surface. The river cuts only a narrow gorge in the Kaibab Limestone, which forms the upper rim of the Grand Canyon downstream. Farther downstream (near the bottom of the photograph), uplift permitted the river to cut much deeper into the rock sequence, and the sequence of profiles across the canyon is similar to the one developed by the computer model. Evidence of the evolution of slope morphology from the canyon itself thus supports the findings of the computer model.

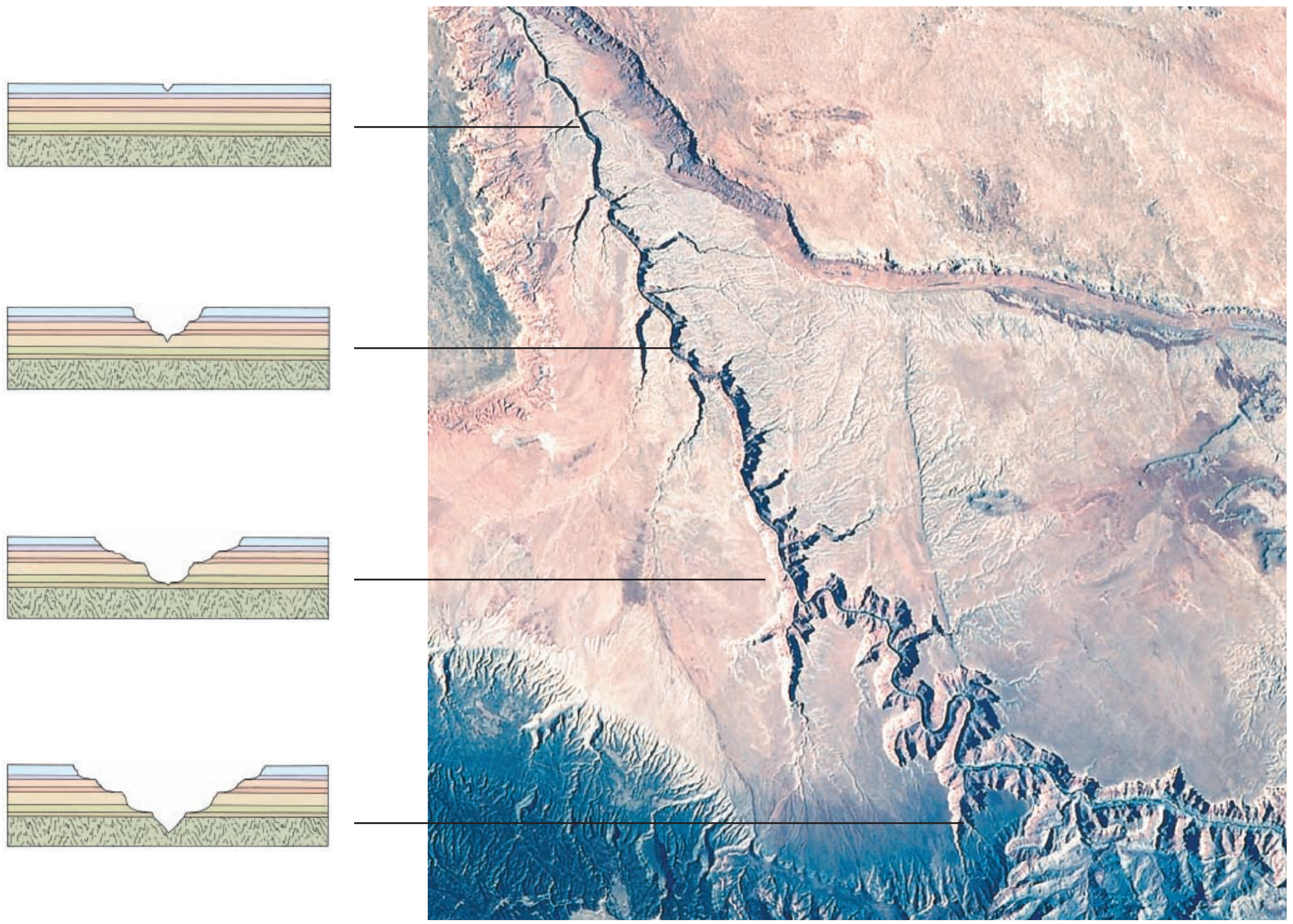


FIGURE 12.23 The effects of erosion of the eastern Grand Canyon are seen in this space photograph. The river flows from Lees Ferry, in the upper left, toward the lower right. At Lees Ferry, the river is just beginning to cut through the sedimentary rock sequence and has produced a profile like the one shown in the computer model. Downstream, uplift has permitted the river to cut deeper, and it has produced a sequence of profiles of alternating cliffs and slopes formed on resistant and nonresistant rock bodies. *(Photograph courtesy of NASA)*

PROCESSES OF STREAM DEPOSITION

In the lower parts of a river system (transporting and dispersing systems), the gradient of a river is very low. As a result, the stream's velocity is reduced, and deposition of much of the sediment load occurs, to create: (1) floodplains, (2) alluvial valleys, (3) deltas, and (4) alluvial fans.

The fact that rivers transport and deposit huge volumes of sediment is apparent in the practical problems of the silting of reservoirs and the maintenance of navigable channels and harbors. Most large rivers are always muddy; in some rivers, the weight sediment sometimes exceeds the weight of water. Sediment is deposited when the velocity of the current falls below the minimum velocity required to keep the particles of a certain size in motion (Figure 12.7). Thus, if a river carrying silt, sand, and gravel is slowed by a gentler gradient, or by entering a lake or the sea, the coarsest particles of the load are deposited first, and progressively finer particles are deposited as the velocity of the current continues to decrease. Deposition of the sediment load in the lower transporting and dispersal segments of a river creates prominent and distinctive landforms. Foremost among these are the great floodplains and alluvial valleys. Farther downstream, where the river enters the sea, most of its load is deposited as huge deltas.

Floodplains

On the gentle slopes of shields and stable platforms, most stream valleys are covered with large quantities of sediment that make up a flat surface over which the stream flows. This surface is called the **floodplain,** and during high floods it may be completely covered with water. Rivers that flow across floodplains are characterized by channels that either meander in sinuous loops or braid in interweaving multiple channels. These differences in channel configurations reflect variations in the type of sediment load and fluctuations in the volume of water. A schematic diagram showing the features commonly developed on a meandering river floodplain is shown in Figure 12.24. It serves as a simple graphic model of floodplain sedimentation.

What major geologic processes operate on a floodplain?

Meanders and Point Bars. All rivers naturally tend to flow in a sinuous pattern, even if the slope is relatively steep, because water flow is turbulent, and any bend or irregularity in the channel deflects the flow of water to the opposite bank. The force of the water striking the stream bank causes erosion and undercutting, which initiate a small bend in the river channel. In time, as the current continues to impinge on the outside of the channel, the bend grows larger and is accentuated, and a small curve ultimately grows into a large **meander** (Figure 12.25). On the inside of the meander, velocity is at a minimum, so some of the sediment load is deposited. This type of deposit occurs on the point of the meander bend and is known as a **point bar.** The two major processes around a meander bend—erosion on the outside and deposition on the inside—cause meander loops to migrate laterally.

River Deposition

Because the valley surface slopes downstream, erosion is more effective on the downstream side of the meander bend; thus, the meander also migrates slowly down the valley (Figure 12.25). As a meander bend becomes accentuated, it develops an almost complete circle. Eventually, the river channel cuts across the meander loop and follows a more direct course downslope. The meander cutoff forms a short but sharp increase in stream gradient, causing the river to completely abandon the old meander loop, which remains as a crescent-shaped lake known as an **oxbow lake** (Figure 12.25).

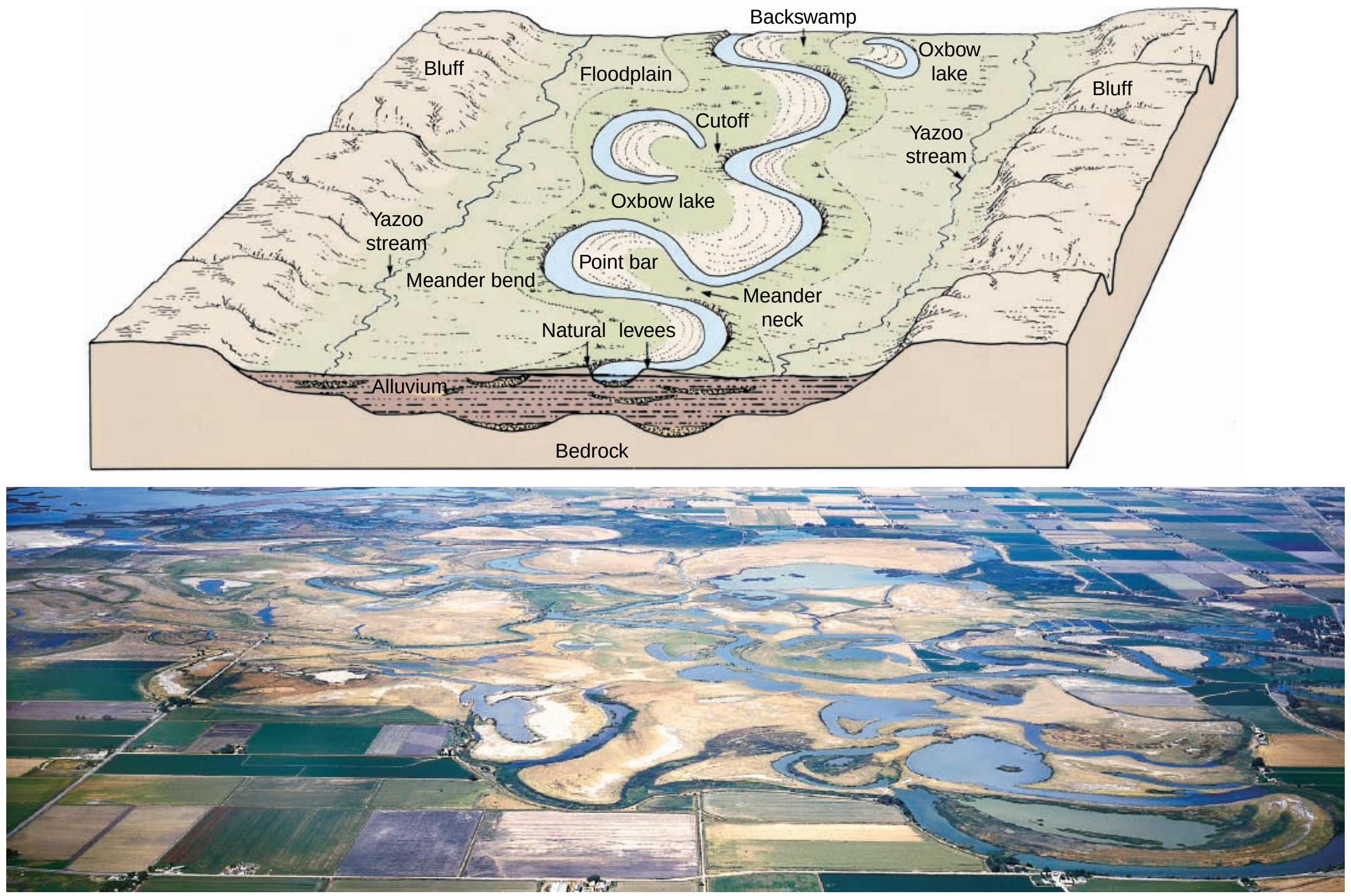


FIGURE 12.24 **The major features of a floodplain** include meanders, point bars, oxbow lakes, natural levees, backswamps, and stream channels. A stream flowing around a meander bend erodes the outside curve and deposits sediment on the inside curve to form a point bar. The meander bend migrates laterally and is ultimately cut off, to form an oxbow lake. Natural levees build up the banks of the stream, and backswamps develop on the lower surfaces of the floodplain. Yazoo streams have difficulty entering the main stream because of the high natural levees and thus flow parallel to it.

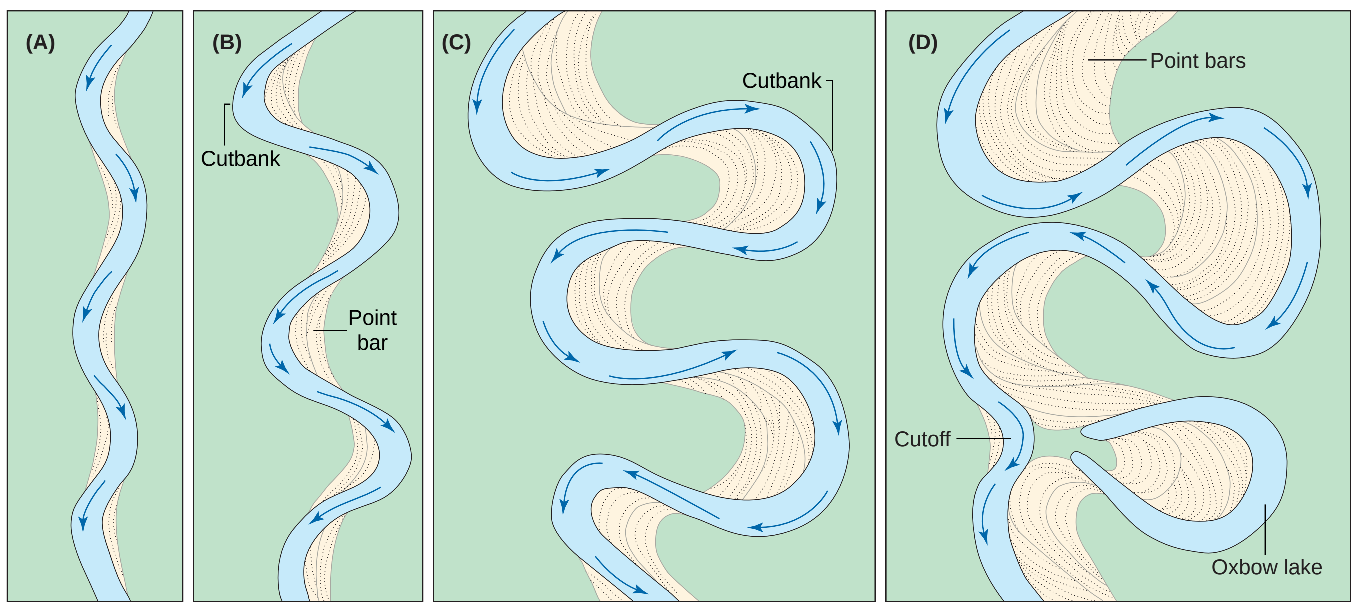


FIGURE 12.25 **Stream meanders evolve** because erosion occurs on the outside of a curved stream channel, where velocity is greatest, and deposition occurs on the inside of the curve, where velocity is low. An irregularity deflects stream flow (A) to the opposite bank and erosion begins. This start the development of a meander loop (B–D). At the same time, sediment is deposited on the inside of the bend, forming point bars. The meander enlarges and migrates laterally (C–D). Continued growth of the meander bends ultimately cuts off the channel and forms an oxbow lake (D).

Natural Levees. Another key process operating on a floodplain is the development of high embankments, called **natural levees,** on both sides of the river. Natural levees form when a river overflows its banks during flood stage and the water is no longer confined to a channel but flows over the land surface in a broad sheet. This unchanneled flow significantly reduces the water's velocity, and some of the suspended sediment settles out. The coarsest material is deposited close to the channel, where it builds up a high embankment. Natural levees grow with each flood. Some grow high enough so that the river channel is higher than the surrounding area (Figure 12.26).

How can a river build its own levees?

Backswamps. As a result of the growth and development of natural levees, much of the floodplain may be lower than the river flowing across it. This area, known as the **backswamp,** is poorly drained and commonly is the site of marshes and swamps. Tributary streams in the backswamp are unable to flow up the slope of the natural levees, so they are forced either to empty into the backswamp or to flow as **yazoo streams,** streams that run parallel to the main stream for many kilometers. Strangely enough, then the highest parts of the floodplain may be along the natural levees immediately adjacent to the river.

Floodplains

The lower Mississippi River is well known for its floodplain features (Figure 12.27). Between Cairo, Illinois, and the Gulf of Mexico, the Mississippi meanders over a broad floodplain, forming high natural levees, oxbow lakes, and backswamps. The dynamics of the river and the changes it can bring about by deposition are illustrated by the fact that, from 1765 to 1932, the river cut off 19 meanders between Cairo, Illinois, and Baton Rouge, Louisiana. Now the level of the Mississippi is controlled by dams and artificial levees, which have modified its hydrology, much as the Nile and Colorado rivers have been artificially manipulated.

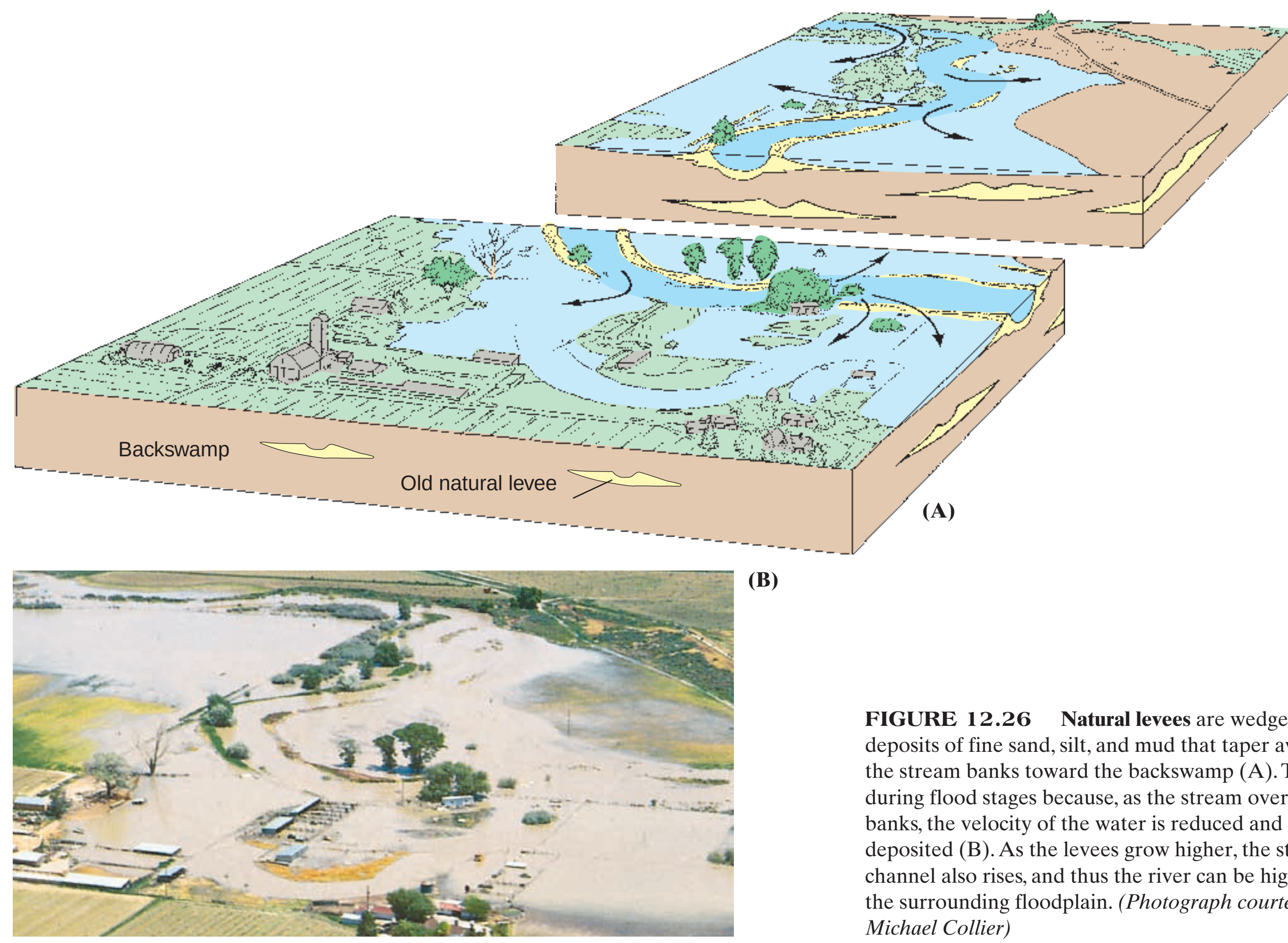


FIGURE 12.26 **Natural levees** are wedge-shaped deposits of fine sand, silt, and mud that taper away from the stream banks toward the backswamp (A). They form during flood stages because, as the stream overflows its banks, the velocity of the water is reduced and silt is deposited (B). As the levees grow higher, the stream channel also rises, and thus the river can be higher than the surrounding floodplain. *(Photograph courtesy of Michael Collier)*

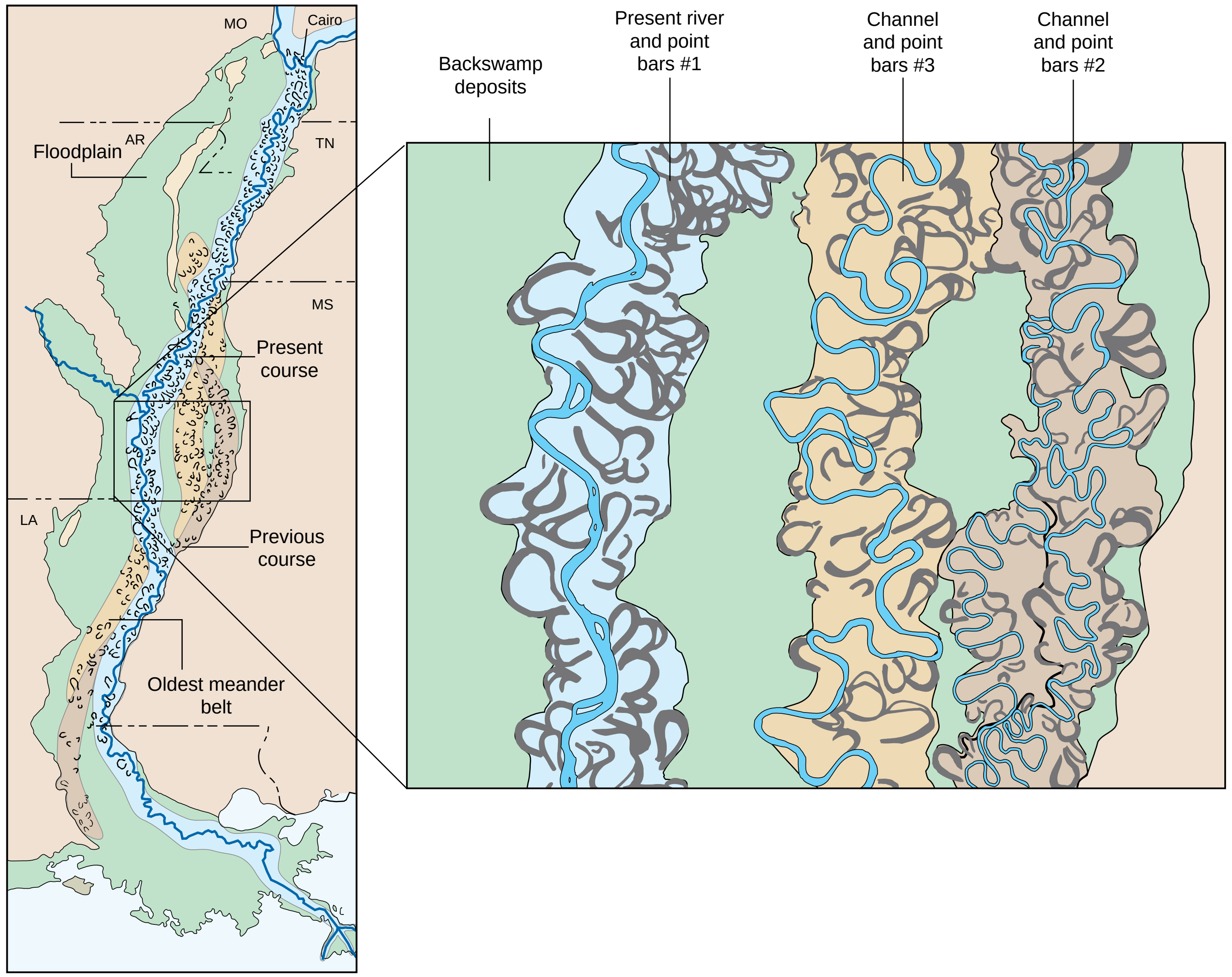


FIGURE 12.27 The floodplain of the Mississippi River extends from Cairo, Illinois, to the sea. It is more than 1000 km long and 200 km wide. The main meander belt has shifted several times during the last few thousand years. Progressively older meander belts are shown in blue, brown, and tan.

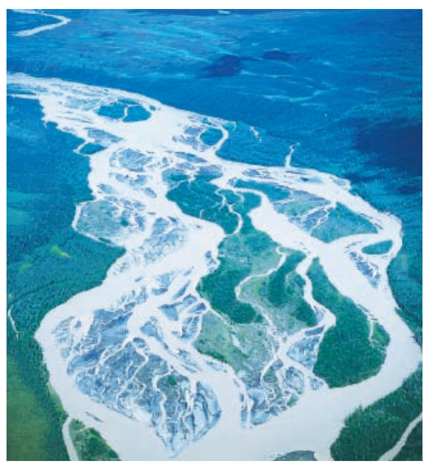


FIGURE 12.28 A braided stream pattern commonly results if a river is supplied with more sediment than it can carry, as at the front of a glacier.

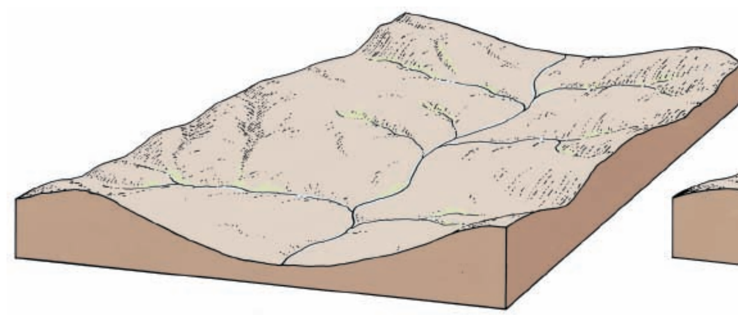
Braided Streams. If streams are supplied with more sediment than they can carry, they deposit the excess material on the channel floor as sand and gravel bars. These deposits may force a stream to split into two or more channels, so the stream pattern forms an interlacing network of braided channels and islands (Figure 12.28). The **braided stream** pattern is best developed in rivers that carry coarse sand and gravel and fluctuate greatly in the volume of water they discharge. These conditions commonly occur in arid or semiarid regions, where the amount of water in a stream varies greatly from season to season, or from storm to storm. Melting ice caps and glaciers also produce favorable conditions for braided streams because the streams in front of the melting ice cannot transport the exceptionally large load of sediment deposited by the glaciers. As a result, deposition occurs in mid-channel and new channels develop. For example, meltwater from the Nabesna glacier of southeast Alaska created the braided stream in Figure 12.28. Moreover, the cold climate near glaciers causes most rivers to freeze during the winter, so the volume of water discharged fluctuates from almost nothing in the winter to spring floods. Compare the channel pattern in this photograph with the meandering channels on the Mississippi River floodplain shown in Figure 12.27.

Alluvial Valleys

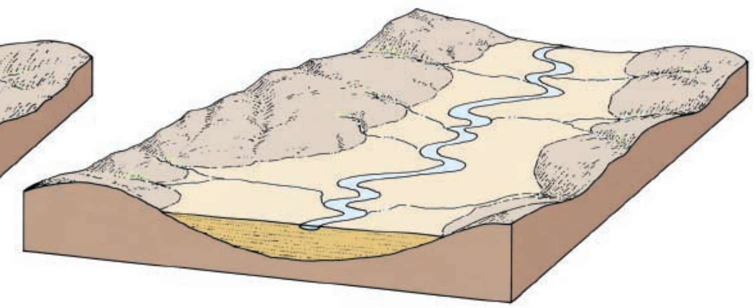
Many streams fill part of their valleys with sediment during one part of their history and then cut through the sediment fill during a subsequent period. This fluctuation in stream processes commonly produces **stream terraces.** Deposition can be initiated by any change that reduces a stream's capacity to transport sediment. These changes include (1) a reduction in discharge (as a result of climatic change or of a loss of water volume due to stream piracy), (2) a change in gradient (caused by a rise in base level or by regional tilting), and (3) an increase in sediment load.

The basic steps in the evolution of stream terraces are shown in Figure 12.29. In (A), a stream cuts a valley by downcutting and **slope retreat.** In (B), changes, such as regional tilting of the land or rising of base level, cause the stream to deposit part of its sediment load and build up a floodplain, which forms a broad, flat valley floor. In (C), subsequent changes (such as uplift or increased runoff) cause renewed downcutting into the easily eroded floodplain deposits, so a single set of terraces develops on both sides of the river. Further erosion can produce additional terraces (D) by the lateral shifting of the meandering stream.

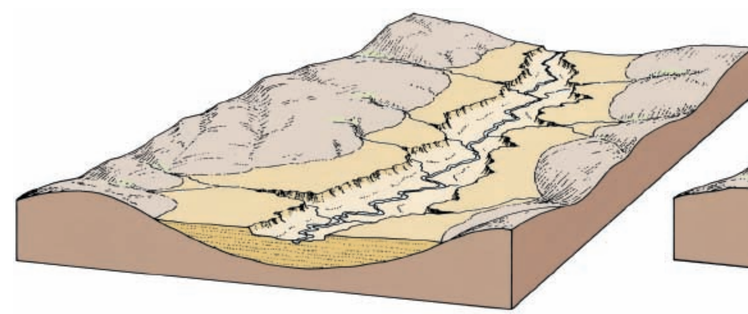
During the last ice age, the hydrology of most rivers changed significantly and produced stream terraces in many river systems. Stream runoff was increased greatly by the melting ice, and large quantities of sediment deposited by the glaciers were reworked by the streams, many of which became overloaded. In addition, the climatic changes accompanying the ice age caused a general worldwide increase in precipitation. As a result, many streams filled part of their valleys with sediment that they are now cutting through to form stream terraces (Figure 12.30).



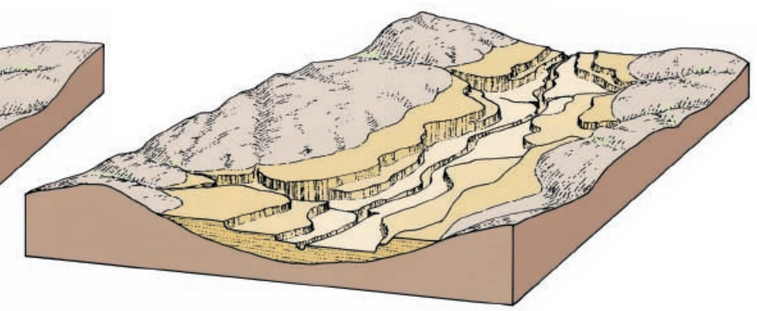
(A) A stream cuts a valley by normal downcutting and headward erosion processes.



(B) Changes in climate base level, or other factors that reduce flow energy cause the stream to partially fill its valley with sediments, forming a broad, flat floor.



(C) An increase in flow energy causes the stream to erode through the previously deposited alluvium. A pair of terraces is left as a remnant of the former floodplain.



(D) The stream shifts laterally and forms lower terraces as subsequent changes cause it to erode through the older valley fill.

FIGURE 12.29 The evolution of stream terraces involves the deposition of sediment in a stream valley, subsequent change in the stream's gradient, and renewed downcutting. These changes can be initiated by various factors that affect a stream's capacity to transport sediment, such as changes in climate, changes in base level, or regional uplift.

FIGURE 12.30 **Stream terraces** along the Pahsimeroi River, Idaho, were formed by recent recurrent uplift. More than seven well-defined terraces can be identified in this area.

Deltas

As a river enters a lake or the ocean, its velocity suddenly diminishes, and most of its sediment load is deposited to form a **delta.** The growth of a delta can be complex, especially for large rivers depositing huge volumes of sediment. However, three major processes are fundamental to the formation and growth of a delta: formation of distributaries, splay development, and avulsion.

Distributaries. The diagrams in Figure 12.31 illustrate the development of distributaries. As a river enters the ocean (or a lake) and the flowing water is no longer confined to a channel, the currents flare out, rapidly losing velocity and flow energy. The coarse material carried by the stream is deposited in two specific areas: (1) along the margins of quiet water on either side of the main channel (deposits build up subaqueous natural levees) and (2) in the channel at the river mouth, where there is a sudden loss of velocity (deposits build a bar at the mouth of the channel). These two deposits effectively create two smaller channels (distributary channels), which can build seaward for some distance. The process is then repeated, and each new distributary is divided into two smaller distributaries. In this manner, a system of branching distributaries builds seaward in a fan-shaped pattern.

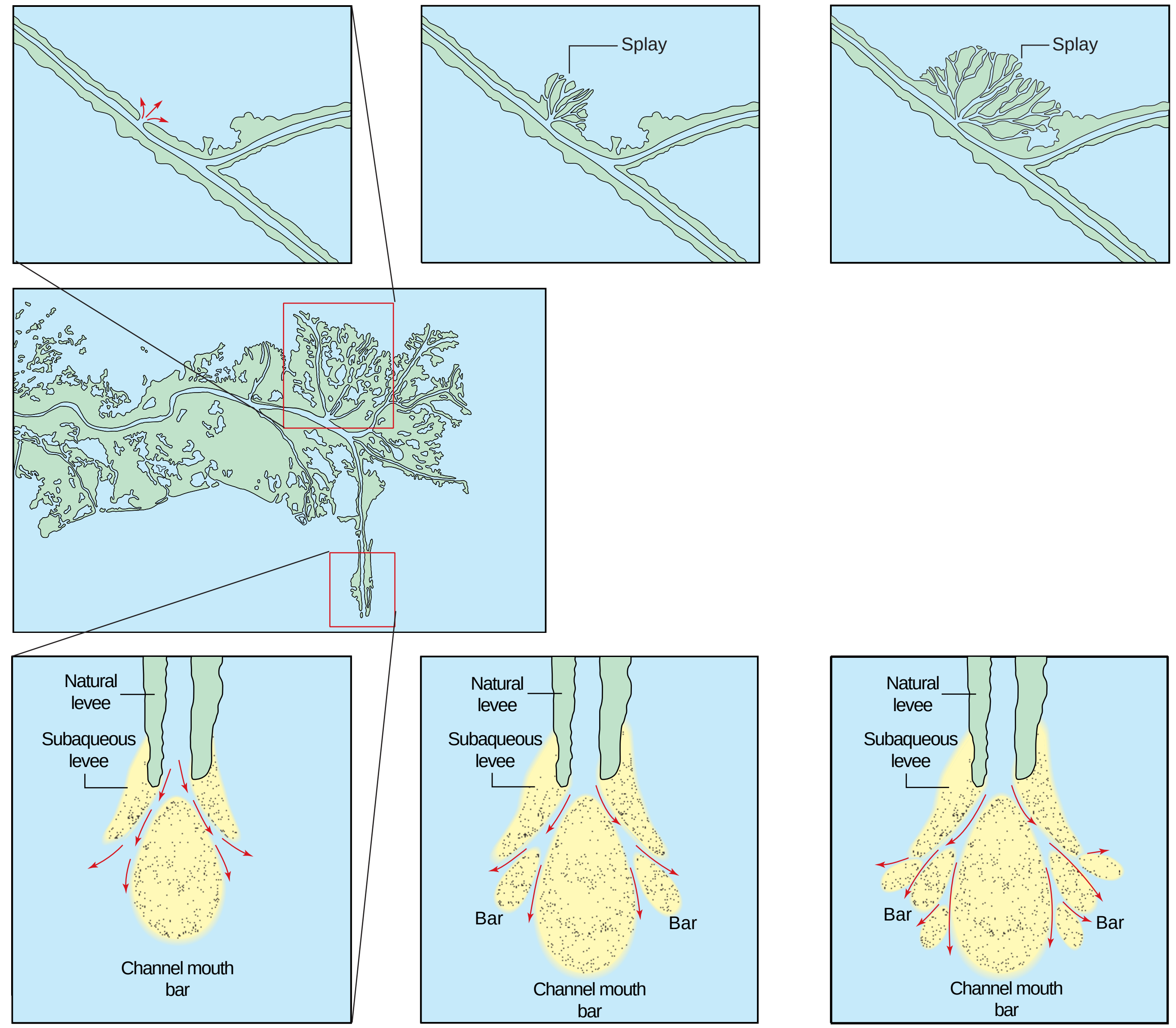
Splays. Figure 12.31 shows how the area between distributaries is filled with sediment. A local break in the levee, a **crevasse,** forms during periods of high runoff and diverts a significant volume of water and sediment from the main stream. The escaping water spreads out and deposits its sediment to form a **splay,** which is essentially a small delta, with small distributaries and systems of subsplays.

The sediment deposited by distributaries and splays is vulnerable to erosion and transportation by marine waves and tides. The growth of a delta is therefore influenced by the balance between the rate of input of sediment by the river and the rate of erosion by marine processes. If waves or tides are strong, the development of distributaries is limited, and the sediment is reworked into bars, beaches, and tidal flats.

(A) Natural levee breached. Part of stream flow diverted to backswamp.

(B) Reduced velocity causes deposition of sediment in a fan-shaped splay.

(C) Growth of splay by development of small distributaries and subsplays.



(D) A bar forms at the mouth of the river channel. Subaqueous levees form.

(E) Stream flow is channeled between bar and natural levees.

(F) Process is repeated, forming branching distributaries.

FIGURE 12.31 **Distributaries and splays** play key roles in the growth of a delta. These sequential diagrams show the evolution of splays (A–C) and distributaries (D–F).

Avulsion. A major phenomenon in the construction of deltas is the shifting of a river's entire course. Distributaries cannot extend indefinitely into the ocean because the river's gradient and capacity to flow gradually decrease. The river, therefore, is eventually diverted to a new course, which has a higher gradient. This diversion generally happens during a flood. The river breaks through its natural levee, far inland from the active distributaries of the delta, and develops a new course to the ocean. The new channel shifts the site of sedimentation to a different area, and the abandoned segment of the delta is attacked by wave and current action. The new, active delta builds seaward, developing distributaries and splays, until eventually it also is abandoned, and another site of active sedimentation is formed. The shifting back and forth of the main river channel is thus a major way in which sediment is dispersed and a delta grows (Figure 12.32).

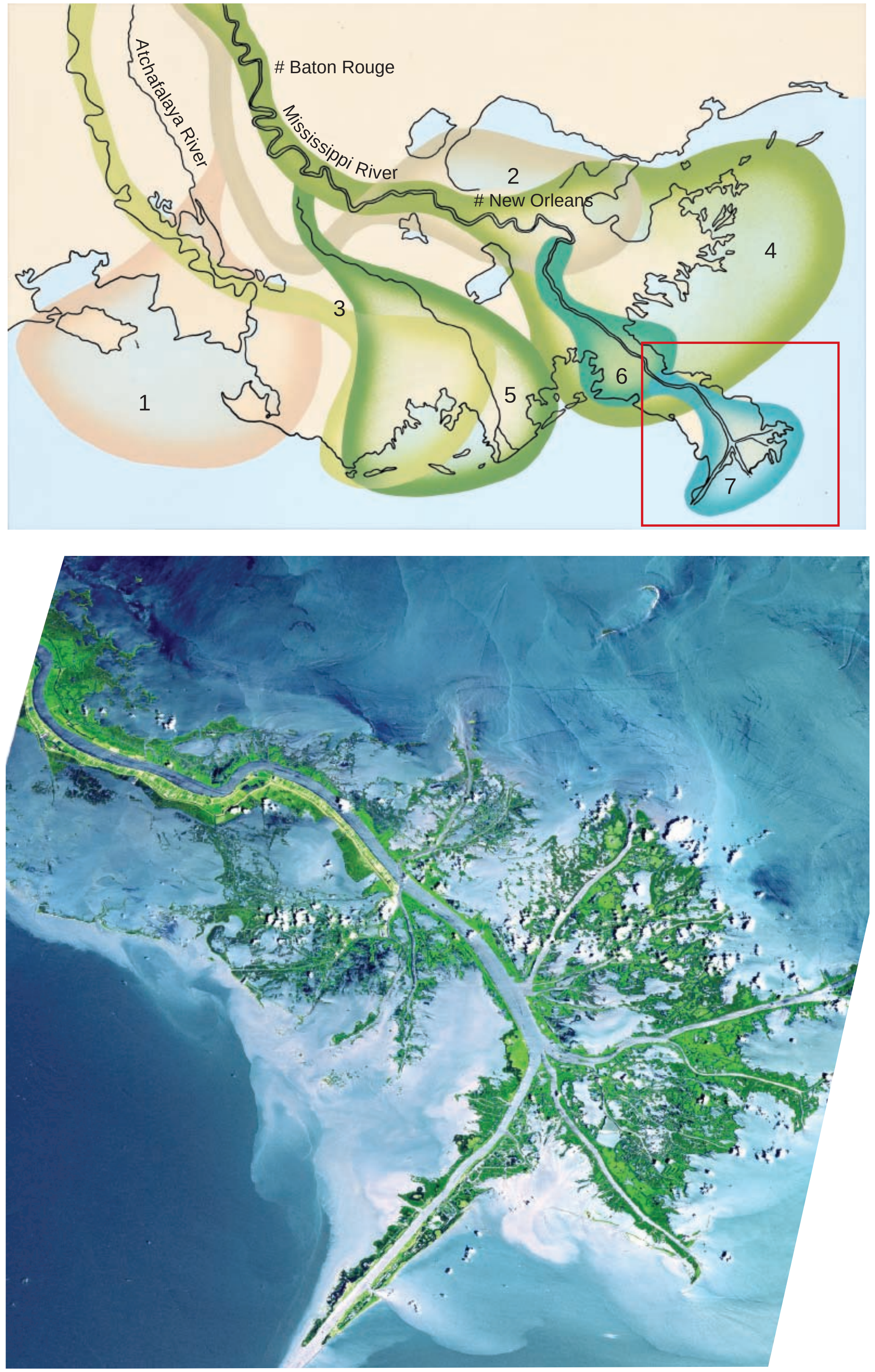
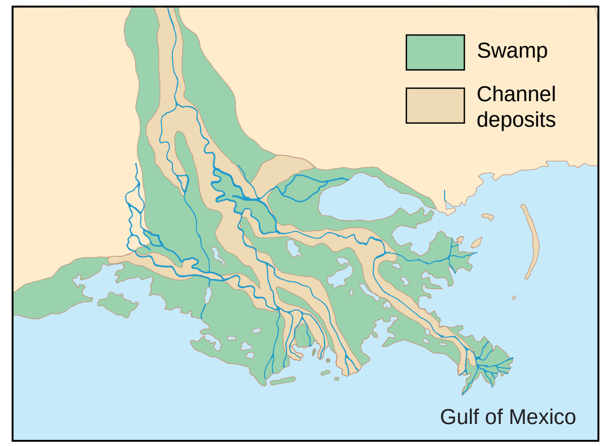


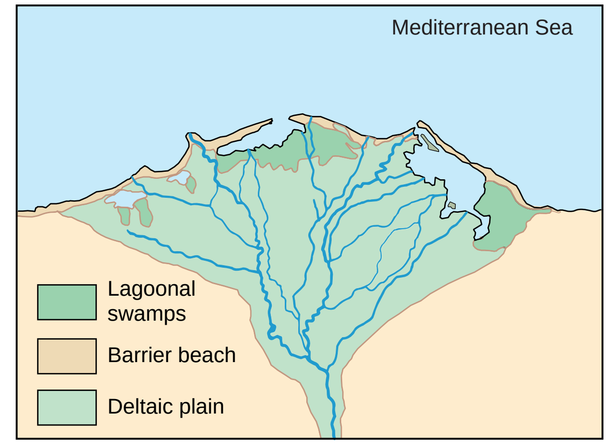
FIGURE 12.32 **The history of the Mississippi Delta** involves repeated avulsion of the main channel, which has formed seven subdeltas. Most of the sediment is deposited in a small sector of the delta front. A major break in the natural levee upstream eventually diverts the entire flow to some other sector, and the process is repeated. Wave action then erodes the inactive bird-foot deltas. Previous subdeltas are indicated by numbers (1–6) according to age; (7) is the present subdelta. The active distributary system (6 and 7) has built a major bird-foot delta in the last 500 years, the details of which are shown in this satellite photograph. *(Courtesy of NASA/GSFC/METI/ERSDAC/JAROS.)*

Types of Deltas. Several types of deltas are illustrated in Figure 12.33. Each shows a different balance between the forces of stream deposition and the forces reworking the sediment (waves and tides). In the Mississippi Delta, processes of river deposition dominate (Figure 12.33A). The delta is fed by the extensive Mississippi River system, which drains a large part of North America and discharges an annual sediment load of approximately 454 million metric tons. The river is confined to its channel throughout most of its course, except during high floods. Most of the sediment reaches the ocean through two or three main distributary channels and has rapidly extended the delta far into the Gulf of Mexico. This extension is known as a **bird-foot delta.**

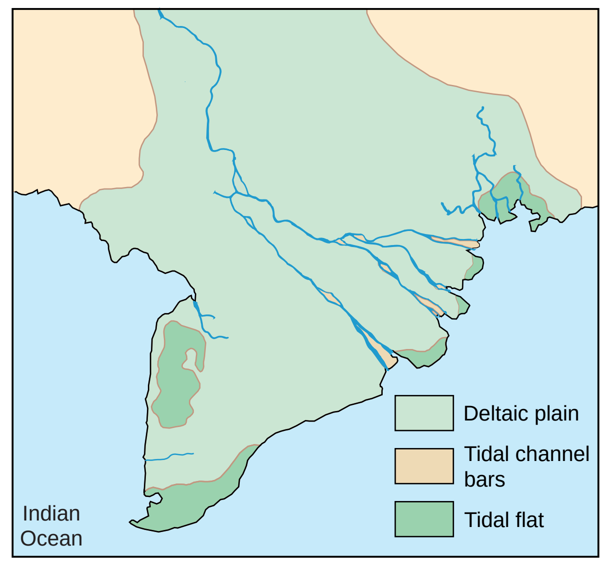
Seven major subdeltas have been constructed by the Mississippi River during the last 5000 years as repeated avulsion occurred in the region between Baton Rouge and New Orleans. These are shown in Figure 12.32. The oldest lobe (1) was abandoned approximately 4000 years ago and since then has been eroded back and inundated. Only small remnants remain exposed today. The successive lobes,



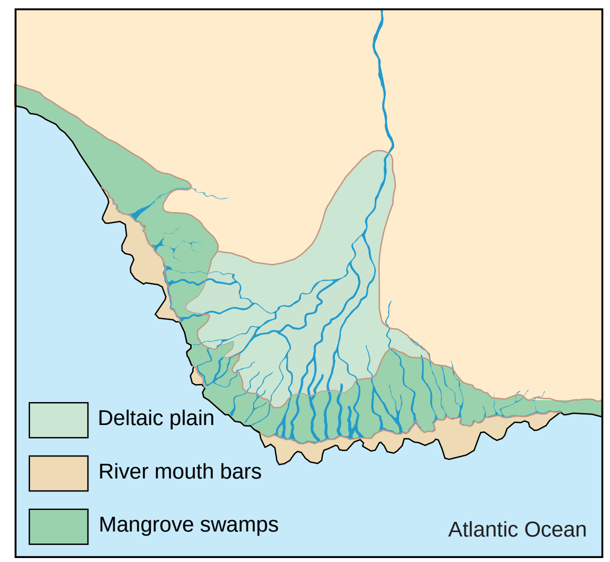
(A) The Mississippi Delta is dominated by fluvial processes that produce a bird-foot extension.



(B) The Nile Delta is dominated by wave action that produces an arcuate delta front.



(C) The Mekong Delta is dominated by tidal forces that produce wide distributary channels.



(D) The Niger Delta has formed where stream deposition, wave action, and tidal forces are about equal. An arcuate delta front and wide distributary channels are thus produced.

FIGURE 12.33 **The shape of a delta** depends on the balance between fluvial and marine processes. The most important processes include the ability of waves and tides to rework the sediment in the delta. The Mississippi, Nile, Mekong, and Niger deltas are dominated by different processes.

or subdeltas (2 to 7), have been modified to various degrees. The abandoned channels of the Mississippi are well preserved and can be recognized on satellite photographs. The currently active delta lobe (7) has been constructed during the last 500 years. River studies show that the present bird-foot delta has been extended as far as the balance of natural forces permits. Without continued human intervention, the Mississippi will shift to the present course of the Atchafalaya River.

The Nile Delta (Figure 12.33B) differs from the Mississippi Delta in several ways. Instead of being confined to one channel, the Nile begins to split up into distributaries at Cairo, Egypt, more than 160 km inland, and fans out over the entire delta. Before construction of the Aswan High Dam, the Nile's annual flood briefly covered much of the delta each year and deposited a new layer of silty mud. Two of the large distributaries have built major lobes extending beyond the general front of the delta, but strong wave action in the Mediterranean redistributes the sediment at the delta front. The reworked sediment forms a series of arcuate barrier bars, which close off segments of the ocean to form lagoons. The lagoons in turn form a subenvironment, which soon becomes filled with fine sediment. The difference between the Nile Delta and the Mississippi Delta is due largely to dissimilar balances between the influx of sediment, which builds bird-foot deltas, and the strength of wave action, which redistributes sediment to form barrier bars.

The Mekong Delta, along the southern coast of Vietnam, is dominated by tidal currents that redistribute sediment in the river channels and along the delta fronts (Figure 12.33C). The distributaries branch into two main courses near Phnom Penh, about 500 km inland. Sediment carried by the river is reworked by tidal current, forming broad distributary channels, a distinctive feature of tide dominated deltas.

The Niger Delta (Figure 12.33D) is a good example of a delta in which the important energy systems are nearly in equilibrium. Stream deposition, wave action, and tidal currents are more evenly balanced there than in the other delta types, so the Niger Delta is remarkably symmetrical.

Alluvial Fans

An **alluvial fan** is a stream deposit that accumulates in a dry basins at the base of a mountain front. Such areas are usually arid and have a large quantity of loose, weathered rock debris on the surface; when rain falls, the streams then transport huge volumes of sediment. Many or most of the streams are intermittent and run for only a short time each year or just during storms. Deposition of the load carried by the streams results from the sudden decrease in velocity as a stream emerges from the steep slopes of the upland and flows across the adjacent basin with its gentle gradient. The channel soon becomes clogged with sediment, and the stream is forced to seek a new course. In this manner, the stream shifts from side to side and builds up an arcuate, fan-shaped deposit (Figure 12.34). Debris flows are also common on alluvial fans. Their coarse unsorted deposits are found interlayered with the stream gravels and sands. As several fans build basinward at the mouths of adjacent canyons, they eventually merge to form broad slopes of alluvium at the base of the mountain range (Figure 12.35).

Although alluvial fans and deltas are somewhat similar, they differ in mode of origin and internal structure. In deltas, sediment is deposited in a body of water. The level of the ocean or lake effectively forms the upper limit to which the delta can be built. In contrast, a fan is deposited in a dry basin, and its upper surface is not limited by water level. Cobbles and gravel in alluvial fans are commonly less rounded than in other stream deposits. The coarse-grained, unweathered, poorly sorted sands and gravels of an alluvial fan also contrast with the fine sand, silt, and mud that predominate in a delta.

FIGURE 12.34 **Alluvial fans** form in arid regions where streams enter dry basins and deposit their sediment load as the stream gradient becomes smaller. This fan is in Death Valley, California.

FLOODS

Flooding is the overflow of water from the stream channel onto adjacent land that is usually dry. It is a natural process in all river systems and has occurred throughout all of geologic time.

Why do floods occur?

Flooding of rivers is not a rare event, but it is often a seasonal occurrence corresponding to prolonged rain or rapid snowmelt. Human populations have always concentrated on deltas and floodplains of major rivers. It is therefore no accident that more than 500 flood stories, like that of Noah in the Bible, from more than 250 peoples or tribes are well documented. Indeed, floods are the most frequent and lethal of all natural disasters.

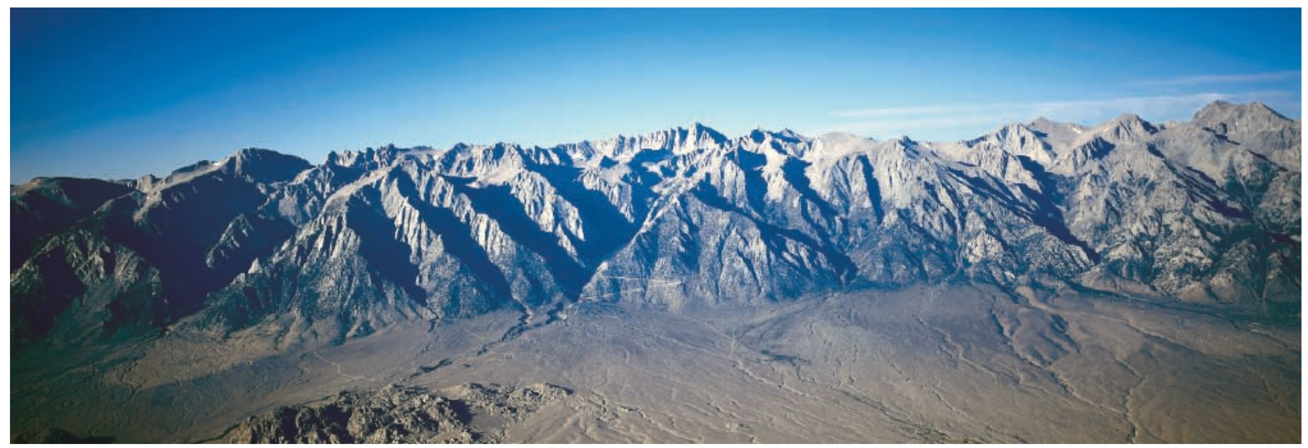


FIGURE 12.35 **Alluvial slopes** develop as fans grow and merge. This photograph of the eastern slope of the Sierra Nevada of eastern California shows large alluvial slopes covering much of the dry basin.

Flooding on Deltas and Floodplains

Flooding

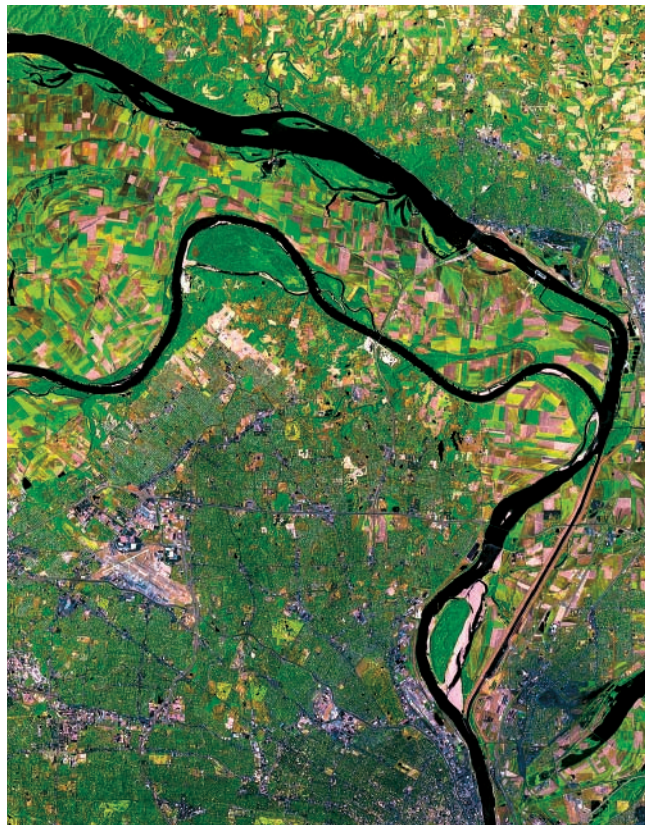
Deltas and floodplains are the regions most susceptible to flooding because in these areas flooding is a fundamental recurring geologic process. Indeed, the deltas and floodplains originate and grow through the process of flooding, and in these areas flooding is as natural as windstorms in a desert. Unfortunately, more than half of the world's population lives along riverbanks, deltas, and seacoasts, where devastating floods are a natural, common process.

Most rivers experience seasonal flooding in which waters overflow their banks and spread out over the floodplain. Exceptional high water can cause extensive flooding over thousands of square kilometers (Figure 12.36). This type of flooding results because rivers that flow over the lowlands and deltas tend to build up high natural levees; the river channel is actually higher than the surrounding area. Ultimately, a river may break through its levee and develop a new course to the sea. Such a breakthrough usually occurs in the delta region of a river where numerous distributaries form over a period of time.

The flood in the upper Mississippi River Basin in 1993 was the greatest flood disaster in U.S. history. Property damage exceeded $10 billion, and millions of acres of productive farmland were under water for weeks. To understand the details of this event, take a moment and study the satellite images of the region around St. Louis, Missouri (Figure 12.36). The geologic setting of the upper Mississippi River Basin is strikingly different from that of the lower basin. In the upper basin, the Mississippi River and its major tributaries (the Missouri and Illinois) flow through relatively deep, narrow valleys throughout much of their course, and their floodplains are like long narrow trenches bounded by steep bluffs. In the lower basin, the floodplain is much wider and is able to accommodate high water. The narrow floodplain in the upper basin was completely covered with floodwater for much of its length, whereas there was no serious flooding in the lower Mississippi River Basin.

Weather in the upper Mississippi River Basin during the latter part of 1992 and continuing into 1993 was highly unusual. Heavy rainfall began in September 1992 and continued for eight months. In some areas, more than three times the "normal" annual rainfall had occurred by June 1993. Soil moisture was therefore at saturation point for essentially the entire region, and reservoirs were at or near maximum capacity. Following this unusually wet spring, excessive precipitation persisted through June and July. Eighty percent of the upper basin received more than 200% normal rainfall for July, and 30% of the area received more than 400%. The flood occurred because the soil throughout the region was saturated, and there was literally no storage capacity in the ground for the incredible amounts of rainfall during the summer.

Recorded history bears grim witness to the destruction flooding can bring. Bangladesh, a country built almost entirely on the huge delta of the Ganges and Brahmaputra rivers, experienced its worst flood of many this century, in which more than 60% of the country (140,000 km^2) was under water. More than 2000 people died and 45 million were uprooted and displaced (Figure 12.37). A similar story is told for other great deltas of the world. The Hwang (Yellow) River in China, for example, periodically overflows its natural levees, causing destruction and misery. In 1887, floodwaters covered more than 130,000 km^2 of the delta's surface, with an estimated loss of life exceeding 1,000,000. In 1991, 200,000 km^2 were flooded; 2000 people died and 1,000,000 were made homeless. The Chinese know all too well the process of flooding in the deltas of their two great rivers, yet they have no choice but to live in the floodplains that have nurtured Chinese civilization for centuries.



(A) The region around St. Louis, Missouri, on July 4, 1988, when the area was experiencing a drought.

(B) The same area on July 18, 1993, at the peak of the flood, when the Mississippi River was 5 m above flood level.

FIGURE 12.36 **The 1993 flood** in the Mississippi River Basin covered vast areas of the floodplain. *(Courtesy of Earth Satellite Corporation/Science Photo Library/Photo Researchers, Inc.)*

FIGURE 12.37 **Floods of the Ganges River** of Bangladesh are caused by the monsoons, which occur between June and September each year. Floods inundate the low-lying delta of the river. *(Brian Blake/John Hillelson Agency)*

Flash Floods

Flash floods are local, sudden, short-lived floods in which great volumes of water rush downstream at high velocities. They frequently occur in the upper reaches of a river, especially in mountain valleys. Flash floods are a major process in developing alluvial fans. Ordinarily, they are caused by brief but heavy rainfall (a cloudburst) that transforms even a dry streambed into a rushing torrent of water and mud. Flash floods are especially likely to occur in regions that have narrow, deeply incised valleys where the river channel is so restricted that an exceptionally high wave of floodwater develops and rushes downstream with tremendous force. Disaster can strike with lightning speed. In the narrow canyons of Zion National Park in Utah, it is not uncommon for a summer storm to cause the river level to rise 30 m.

The flash flood on the Big Thompson River that drains part of the Colorado Rockies near Denver is a classic example. Spawned by 25 to 30 cm of rainfall from a violent cloudburst on the night of July 31–August 1, 1976, the downpour transformed a small mountain stream into a raging torrent of muddy water. The wall of water swept down the canyon, demolishing nearly everything in its path, including canyon highways, bridges, homes, and commercial buildings. At least 150 people perished and property damage exceeded $50 million.

It is clear that the greatest cause of flood damage is the choice (or necessity) of humans to build near rivers. Flooding is a natural geologic process that has become a hazard to humans only since they have built and developed communities in mountain valleys, floodplains, and deltas.

RIVERS, CLIMATES, AND PLATE TECTONICS

The evolution of the major rivers of the world is influenced directly and indirectly by plate tectonics and by climate zones.

How is the distribution of major rivers related to climate?

In previous sections of this chapter, we considered river systems on a local basis: how they erode, transport, and deposit material. The major rivers of the world have other features, of a much larger scale, that are related to the global patterns of the hydrologic and tectonic.

Climate and River Systems. A glance at a drainage map of the world may give a first impression that the drainage of the continents is haphazard and unsystematic. Rivers appear to flow in any direction, in an almost unlimited variety of patterns. Upon further study, however, some system becomes apparent in the locations of the major rivers, their tributaries, and the patterns they form.

Figure 12.38 shows the locations of the world's major rivers and the relative sizes of their deltas. The major rivers are found on broad, gently sloping platforms that lie near the equator— where there is maximum rainfall (see Figure 9.5). Likewise, the sizes of the deltas formed at the mouths of the major rivers of the world are controlled by the size of the drainage basins, elevation of the land, and climate (which controls the amount of surface runoff). Maximum sediment load occurs in large rivers that drain mountainous topography in a humid climate. The world's largest deltas are built by the Amazon, Tigris-Euphrates, Ganges, Mekong, and Hwang Ho. In addition, there is a common association of many rivers with a submarine canyon and a huge submarine fan built out onto the abyssal plains in the deep-ocean basin. A submarine fan, like a delta built at a river mouth, is an indication of the vast amount of erosion accomplished by the work of a river system.

It is also apparent from Figure 12.38 that large areas of the continents do not have major river systems. Arid and semiarid low-latitude deserts, such as the Sahara in North Africa, the Kalahari in South Africa, and the great desert in Australia, are the most obvious examples (see Figure 9.20). Sand seas cover much of them.

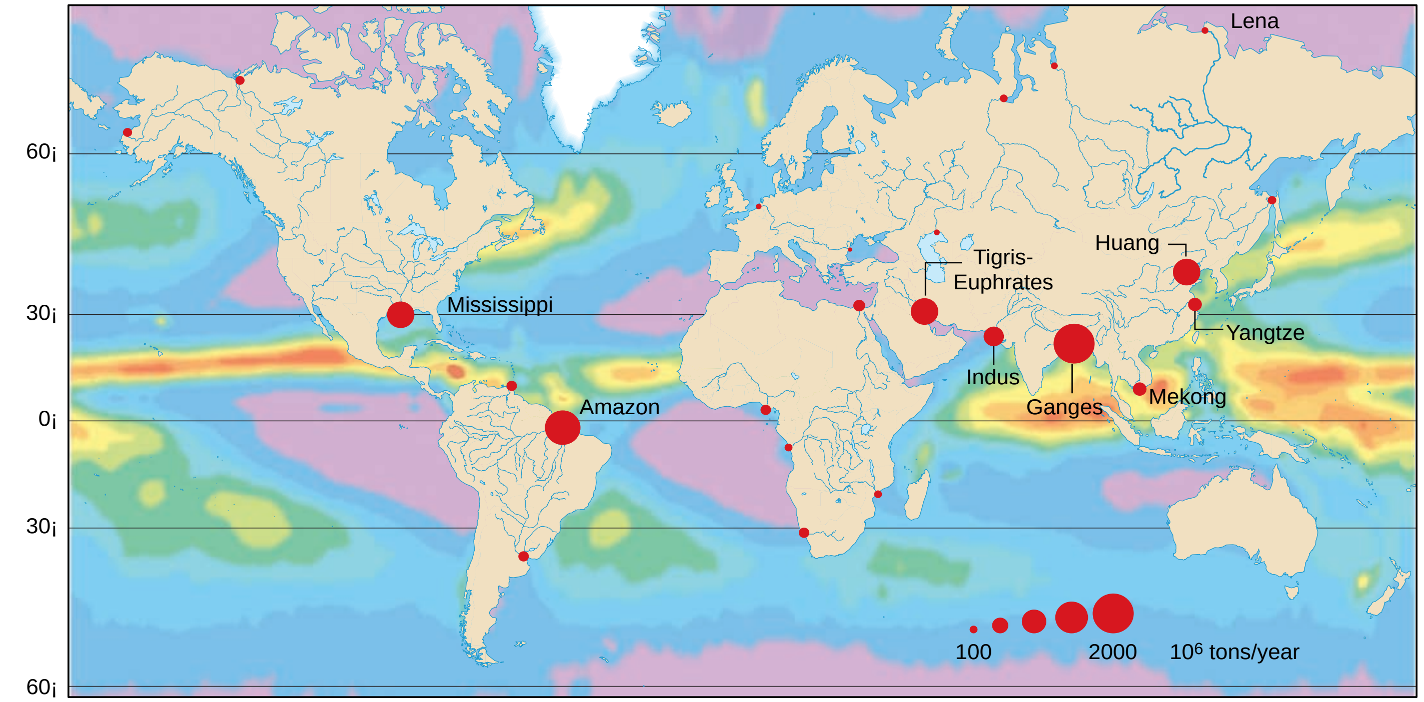


FIGURE 12.38 The world's largest rivers transport vast volumes of sediment, most of which is deposited as huge deltas. The size of the deltas is partially controlled by climate. Most of the large rivers are in the tropics or originate in the tropics where precipitation is highest (red higest to purple lowest precipitation).This size of the circles shows the annual discharge of sediment for the largest drainage systems of the world.

Low surface runoff is not confined to the low-latitude deserts, however. Large river systems are not found in the polar regions of North America and Europe. There are several reasons for this. First, these areas were covered with glaciers during the ice age, which ended only a few thousand years ago. Previous drainage systems were obliterated as the glaciers expanded over the region, and there has not been sufficient time for new integrated drainage systems to develop. Second, large tracts of the polar regions are, in fact, arid and have low precipitation (see Figure 12.1 and Figure 9.5).

Humid areas underlain by porous limestone have poor drainage because solution activity develops a network of subterranean caverns and enlarged fractures, which divert the drainage to the subsurface. Many of these areas have no integrated drainage systems, despite their humid climate. Parts of Kentucky, Florida, and Mexico's Yucatan Peninsula are in this category. Large rivers do not develop on tropical islands because the catchment areas are too small even though rainfall is very high.

River Systems and Plate Tectonics. Plate tectonics is a fundamental factor in the origin and evolution of Earth's major river systems. As shown in Figure 12.39, tectonics can influence rivers in a variety of ways. The most obvious is that tectonism creates the principal relief of continents such as mountain melts along plate margins and continental tilt. The convergence of the Pacific plates with North and South America produced a long linear mountain belt.with an eastward continental tilt. The result is that most of the drainage of the Americas is a sample pattern away from the converging margin toward the passive margins of the Atlantic Ocean (purple arrows). The Amazon River of South America and the pre-glacial drainage of North America are classic examples of this type of tectonic control. Perhaps this was the most common drainage pattern in the geologic past.

Even more impressive are the mountains and highlands extending from France to the South China Sea, a distance of more than 13,000 km. This highland resulted from India and Africa impinging on Eurasia. This created a subradial drainage of the great rivers of Asia (purple). In fact, seven of the ten largest rivers originate in the Himalayan orogenic belt.

Associated with continent-to-continent collision are depressions or basins, downwarps of the crust, parallel to the mountain belt. Drainage commonly develops in the downwarp parallel to the axis of the mountain belt. The Ganges, Indus, Tigris-Euphrates, and Danube are good examples (red arrows).

Continental rifting is one of the most direct and obvious ways in which drainage can be modified by plate tectonics. The most recent rivers generated by rifting are those associated with the African Rift Valleys (black arrows) and the Red Sea. Older rift-generated drainages are the rivers flowing down the escarpments formed when Pangaea broke up and the various continental fragments drifted apart. The rift-generated rivers are commonly associated with basalt extruded along the rift system. The great escarpments along the west coast of India, southern and western Africa, and the eastern coast of South America, as well as eastern Australia were formed during the breakup of Pangaea and rivers flowing down the shoulders of the escarpments are among the oldest rivers in the world.

Modification of Basic River Pattern. Many exceptions and modifications to this basic pattern are influenced by tectonics. Continental rifting effectively beheads or dismembers a previously established river system. Also, if rifting or subsidence occurs in the shield or platform, it will tend to focus and orient the trunk system of the drainage. Examples are the lower Niger, Amazon, Parana, and lower Mississippi rivers.

Indirectly, the tectonics of a continent influence drainage patterns because folded rocks produced by crustal deformation create zones of alternating hard and soft rock, parallel to the trend of the mountain belt. Headward erosion follows the zones of weakness and modifies the pattern so that large segments of a river flow parallel to the structural trends of the folded mountain belt. The Mekong (Vietnam) and Irrawaddy (Burma) rivers in Southeast Asia are examples.

Do rivers have histories? How is the history of a river related to plate tectonics?

Volcanic activity is another method by which the tectonic system modifies a river's drainage pattern. Extrusion of flood basalts can obliterate the preexisting drainage system. A new pattern is then established on the volcanic surface or along the margins of the flows.

The drifting of a continent into a new climatic zone is yet another way in which tectonic activity modifies a river system. As a continent drifts into the low latitudes, precipitation is greatly reduced, and wind-blown sand can completely cover large parts of the previously established drainage. Proof of this type of modification was recently discovered in radar images of parts of the Sahara, made during a flight of the space shuttle *Columbia* (Figure 12.40). These images show a large and extensive ancient drainage system now buried beneath the sand.

The drifting of continents into cold climatic zones may cause similar destruction of a substantial part of the drainage system if glaciers develop and cover the continent. Continental glaciation obliterates the drainage system beneath it and forces the major rivers to establish a new course along the margins of the ice. After the continental ice sheet retreats, a new and complex drainage pattern is integrated through a system of overflowing ponds and lakes.

Age of Rivers. The age and history of a river system are fundamental questions, but the answers may be difficult to determine. We may consider the time of the origin of a river to be the earliest date at which a continuous system drained the region in question. We may consider a river to date from the last marine regression, the last significant tectonic uplift, the termination of lava extrusion, or the waning of an ice sheet. All produce new surfaces upon which a drainage system may evolve. A river could be terminated by a new marine invasion, new tectonism, glaciation, volcanic extrusion, or expansion of a sand sea, but it is not always that simple. In fact, some of today's major river systems may date back to the early Cenozoic Era, 40 to 50 million years ago.

However, various parts of a river system originate and evolve at different times and in different ways, so we cannot establish a precise time when an entire river system originated. Very few rivers (and certainly no major ones) begin or end without some relationship to the drainage system that preceded them. Instead, a drainage system continually evolves by headward erosion and stream capture, adjustment to the structure of the underlying rocks, and modifications related to marine transgressions, continental glaciation, desert sand, and continental rifting. As the system continually evolves, each period of its history inherits something from the preceding conditions. The reason rivers continue to evolve is that the hydrologic system is continuous. Uplift of a mountain belt cannot divert or change the course of a river because a river has the capacity to downcut its channel much faster than uplift occurs. A river's history is a history of the landscape over which it flows.

In all probability, the great Amazon is not the largest river the world has seen. Larger rivers probably drained Pangaea, the ancient landmass that existed about 200 million years ago, before the present continents were outlined and drifted apart. The ancestral Congo, for example, could have flowed across South America before rifting.

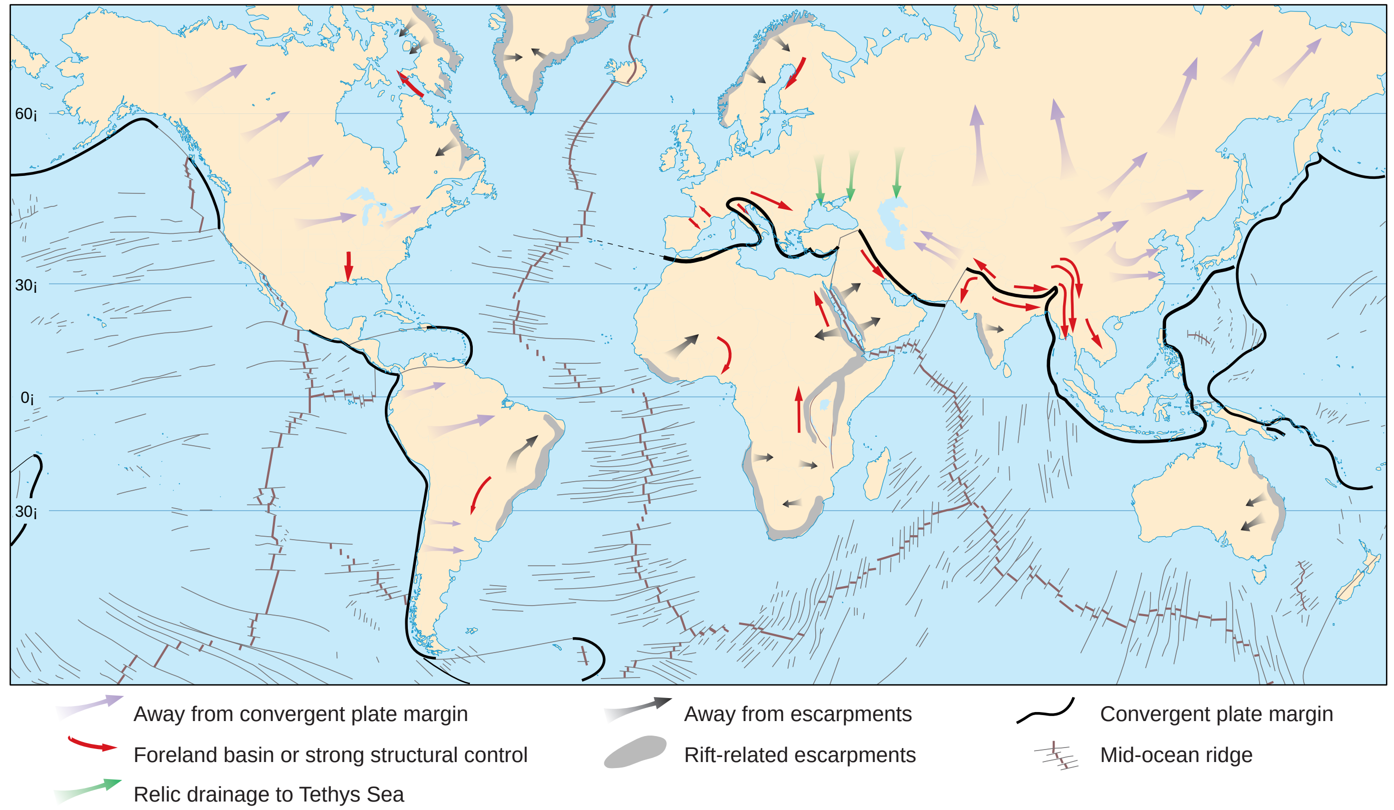


FIGURE 12.39 The relationship between river systems and plate tectonics is shown on this map of plate boundaries and the flow direction of the major rivers. Convergent plate boundaries (purple arrows) have had the greatest influence on the drainage of Eurasia and the Americas where drainage is away from the mountain belt on the convergent margin. Downwarped basins and tightly folded mountain belts create drainage parallel to the orogenic belt (red arrows). Divergent plate margins commonly create drainage away from the rift system (black arrows).

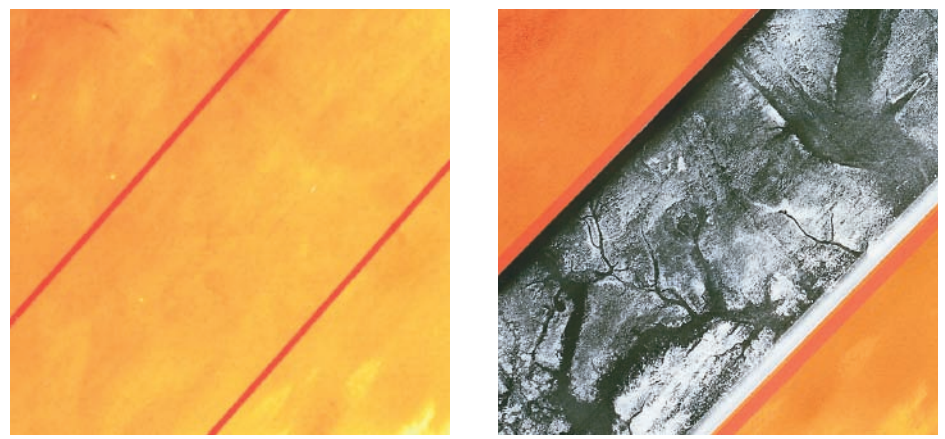
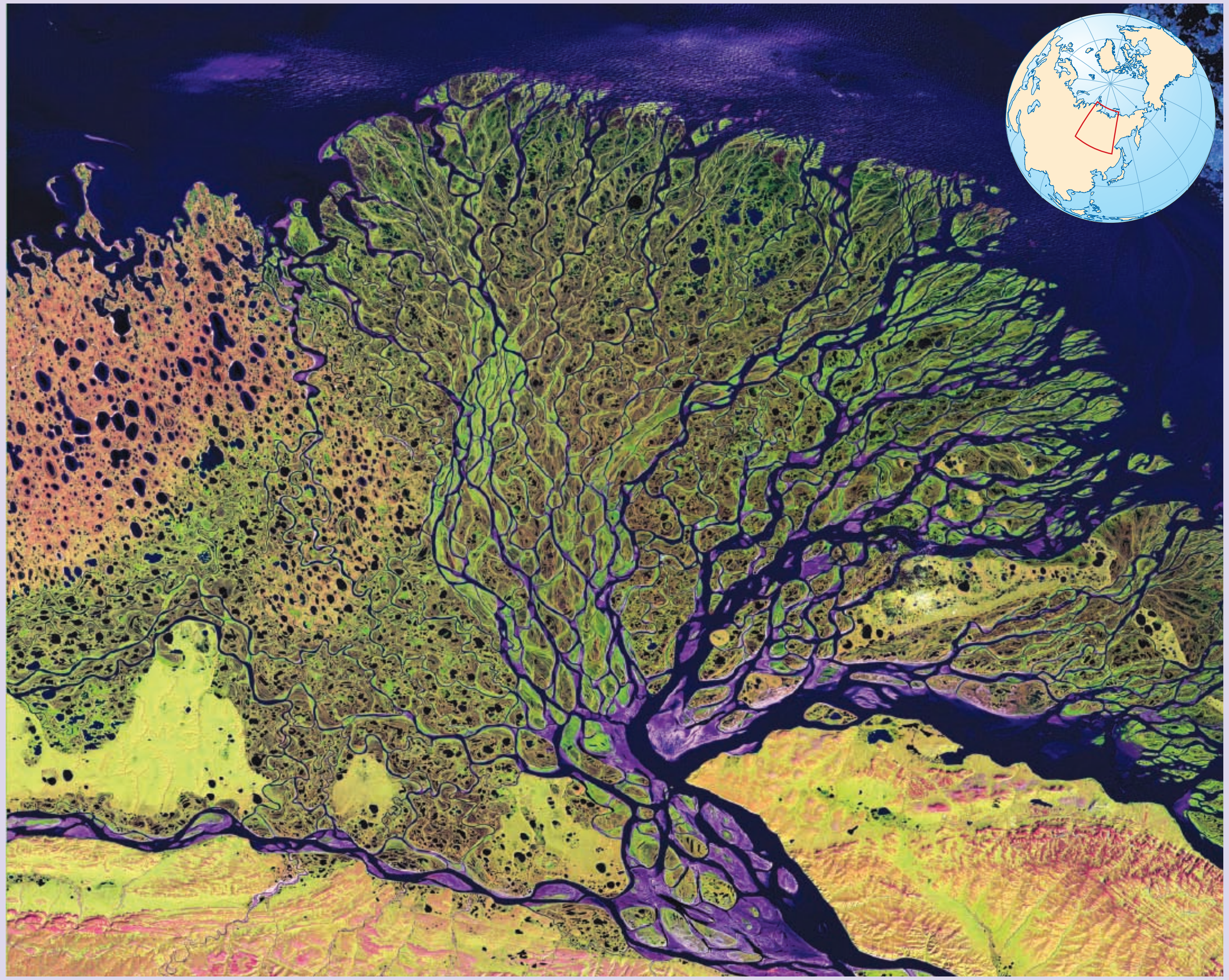


FIGURE 12.40 Ancient river systems in the Sahara Desert are now buried under sand but are revealed by radar imagery made during a flight of the space shuttle. On a satellite image, the present sand desert surface is yellowish orange (top) and gives no hint of a river drainage. The black-and-white radar image cutting diagonally across the picture on the right covers an area about 50 km wide and 300 km long. The largest valley on the image is as wide as the present Nile River valley and represents millions of years of erosion when the Sahara had a much wetter climate. *(Courtesy of U.S. Geological Survey)*

GeoLogic Russia's Lena River Delta



The delta of the Lena River in northern Russia clearly shows many of the processes of delta building. Sediment picked up by a huge tributary system flows as much as 4,000 km before it is deposited here as a large fan-shaped delta.

Observations

1. The river freezes over during the winter, but during spring high runoff transports large volumes of sediment.
2. The seasonal fluctuation in stream runoff plus the load of coarse gravel develop braided stream channels.
3. Channel bars are abundant and numerous distributary bars develop where the river channel approaches the sea.
4. When the major river channel shifts part of the delta becomes inactive and no additional sediment is deposited. Numerous small lakes associated with permafrost activity form on the abandoned part of the delta (on the west).
5. The Arctic Ocean is frozen during the long winter so wave action along the delta front is limited.

Interpretations

The Lena Delta is dominated by fluvial processes. As the river encounters the ocean, its velocity slows and the clastic sediment it carries drops out to make channel mouth bars that split the channel and create a branching system of distributaries. Avulsion moves the course of the major stream and, as a result, the focal point of deposition moves back and forth across the delta. Today, the eastern part of the Lena delta is most active and the northwestern part has been abandoned. The inactive part of the delta has been reshaped over into a series of irregular ponds by the repeated freezing and thawing, swelling and collapsing, of the water-saturated sediment. Unseen in this vertical view, is the thick (1 to 5 km) wedge of clastic sediment that has accumulated on the continental margin. Deltas are major sedimentary environments that contribute to the continuing growth of the continents.

Courtesy U.S. Geological Survey and EROS Data Center

KEY TERMS

abrasion (p. 310)
alluvial fan (p. 326)
avulsion (p. 323)
backswamp (p. 319)
base level (p. 304)
bed load (p. 303)
bird-foot delta (p. 325)
braided stream (p. 320)
capacity (p. 304)
collecting system (p. 299)
competence (p. 304)
crevasse (p. 322)
delta (p. 322)
dendritic drainage pattern (p. 299)
discharge (p. 302)
dispersing system (p. 301)
dissolved load (p. 304)
distributary (p. 301)
divide (p. 299)
downcutting (p. 310)
drainage basin (p. 299)
floodplain (p. 317)
graded stream (p. 305)
gradient (p. 302)
headward erosion (p. 311)
longitudinal profile (p. 302)
meander (p. 317)
natural levee (p. 319)
oxbow lake (p. 317)
point bar (p. 317)
pothole (p. 310)
river system (p. 299)
saltating (p. 303)
slope retreat (p. 321)
splay (p. 322)
stream piracy (p. 312)
stream terrace (p. 321)
superposed stream (p. 313)
suspended load (p. 303)
threshold velocity (p. 304)
transporting system (p. 300)
trellis drainage pattern (p. 313)
tributary (p. 299)
turbulent flow (p. 303)
yazoo stream (p. 319)

REVIEW QUESTIONS

1. Explain the reasons for concluding that stream action (running water) is the most important process of erosion on Earth.
2. Describe and illustrate the three major subsystems of a river.
3. Draw a diagram showing the general nature of transportation of (a) bed load, (b) suspended load, and (c) dissolved load.
4. Explain the role of flow velocity in the transportation and deposition of stream sediment.
5. Explain the concept of equilibrium in river systems, and cite several examples of how streams adjust to attain equilibrium.
6. How does urbanization affect surface runoff?
7. Explain how a stream cuts a valley through solid bedrock.
8. What is headward erosion? Why does it occur?
9. Explain the process of stream piracy, and cite examples of how it modifies a drainage system.
10. How does a stream system grow longer?
11. Name and describe the important landforms associated with floodplain deposits.
12. Describe the steps involved in the growth of a stream meander and the formation of an oxbow lake.
13. How does a point bar develop?
14. Explain the origin of natural levees.
15. What conditions are conducive to the development of braided streams?
16. Describe and illustrate the steps in the development of stream terraces.
17. Explain how a delta is built where a stream enters a lake or the sea.
18. Outline the history of the Mississippi Delta.
19. Make a series of sketches to show the form of a delta in which (a) fluvial processes dominate, (b) wave processes dominate, and (c) tidal processes dominate.
20. Explain how an alluvial fan is built.
21. What role does climate play in shaping river systems?
22. Contrast the nature of a river system that flows from a mountain belt toward a convergent plate margin and one that flows toward a passive continental margin.

ADDITIONAL READINGS

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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:

- Animations of floodplain processes
- Video clips of flooded river valleys
- Slide shows with examples of river erosion and deposition
- A direct link to the Companion Website