Introduction to Ocean Sciences

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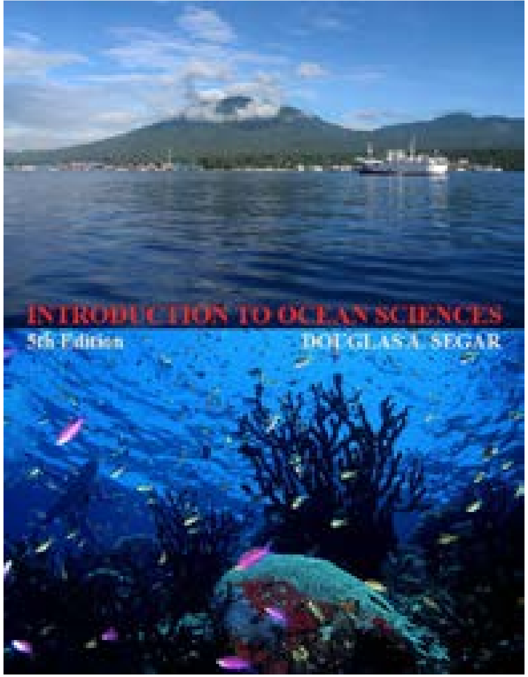

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CHAPTER 11

Coasts

CRITICAL CONCEPTS USED IN THIS CHAPTER

CC2 Isostasy, Eustasy, and Sea Level
CC4 Particle Size, Sinking, Deposition, and Resuspension
CC8 Residence Time

This beautiful rocky coastline is in the Point Lobos State Park just south of Monterey, California. In the distance, at the far side of the bay shown in the image, is the wide, white sand beach of Carmel, California.

A large proportion of the world's population lives within a few tens of kilometers of a **coast.** In 2018 in the United States, 40% of the total population, or more than 128 million people, lived in counties directly on the shoreline. Tens of millions more Americans live in counties that, while not shoreline counties, are close to the coast or a navigable river. The concentration of human populations on or near the coast reflects the importance of the **coastal zone** to civilization.

The term *coast* has various definitions, but it is generally considered to be the strip of land between the **coastline** (where water meets land) and the inland location where there is no longer any environmental influence of the ocean. We build houses, factories, piers, docks, and marinas in this zone, primarily because the ocean is valuable for transport, recreation, and disposal of wastes, particularly treated sewage. In a human lifetime, most coastlines seem fixed and permanent. In reality, they are in a continuous state of change and movement. This chapter examines different types of coasts and the processes that form and reshape them. It also examines human attempts to control and mold the coasts, and the futility of many such efforts.

PROCESSES THAT FORM AND MODIFY THE COASTLINE

All coasts change in character along their length, but their general character tends to be similar for thousands of kilometers. Figure 11-1 shows just some of the various coast types of the United States and Canada. Each type is continuously changing in response to various processes that form and modify it over decades, centuries, and millennia.

Most coasts can be classified as either **erosional** or **depositional,** depending on whether their primary features were created by erosion of land or deposition of **sediments.** Erosional coasts develop where the **shore** is actively eroded by wave action or where rivers or **glaciers** caused erosion when sea level was lower than it is now. Depositional coasts develop where sediments ac-


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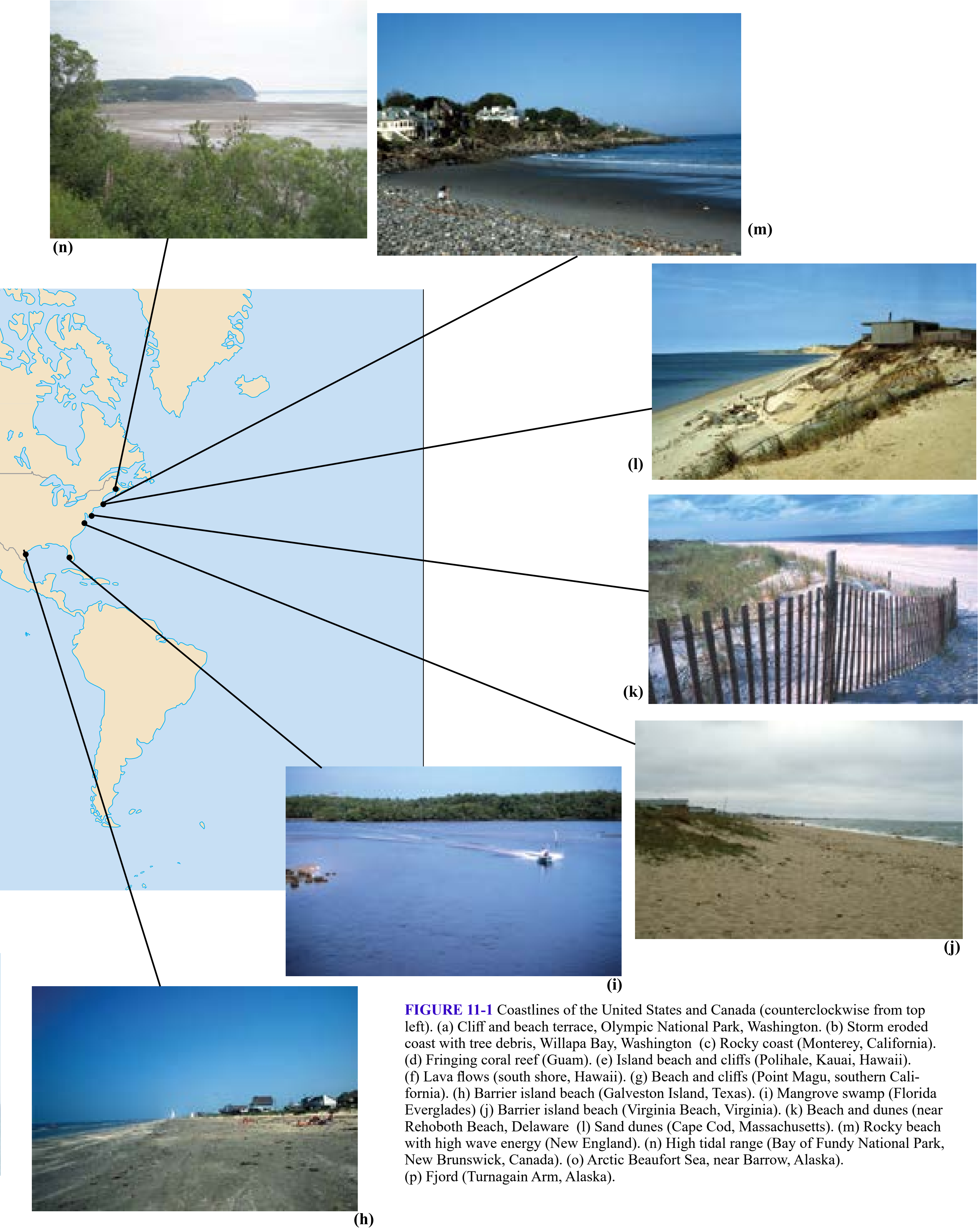


FIGURE 11-1 Coastlines of the United States and Canada (counterclockwise from top left). (a) Cliff and beach terrace, Olympic National Park, Washington. (b) Storm eroded coast with tree debris, Willapa Bay, Washington (c) Rocky coast (Monterey, California). (d) Fringing coral reef (Guam). (e) Island beach and cliffs (Polihale, Kauai, Hawaii). (f) Lava flows (south shore, Hawaii). (g) Beach and cliffs (Point Magu, southern California). (h) Barrier island beach (Galveston Island, Texas). (i) Mangrove swamp (Florida Everglades) (j) Barrier island beach (Virginia Beach, Virginia). (k) Beach and dunes (near Rehoboth Beach, Delaware (l) Sand dunes (Cape Cod, Massachusetts). (m) Rocky beach with high wave energy (New England). (n) High tidal range (Bay of Fundy National Park, New Brunswick, Canada). (o) Arctic Beaufort Sea, near Barrow, Alaska). (p) Fjord (Turnagain Arm, Alaska).

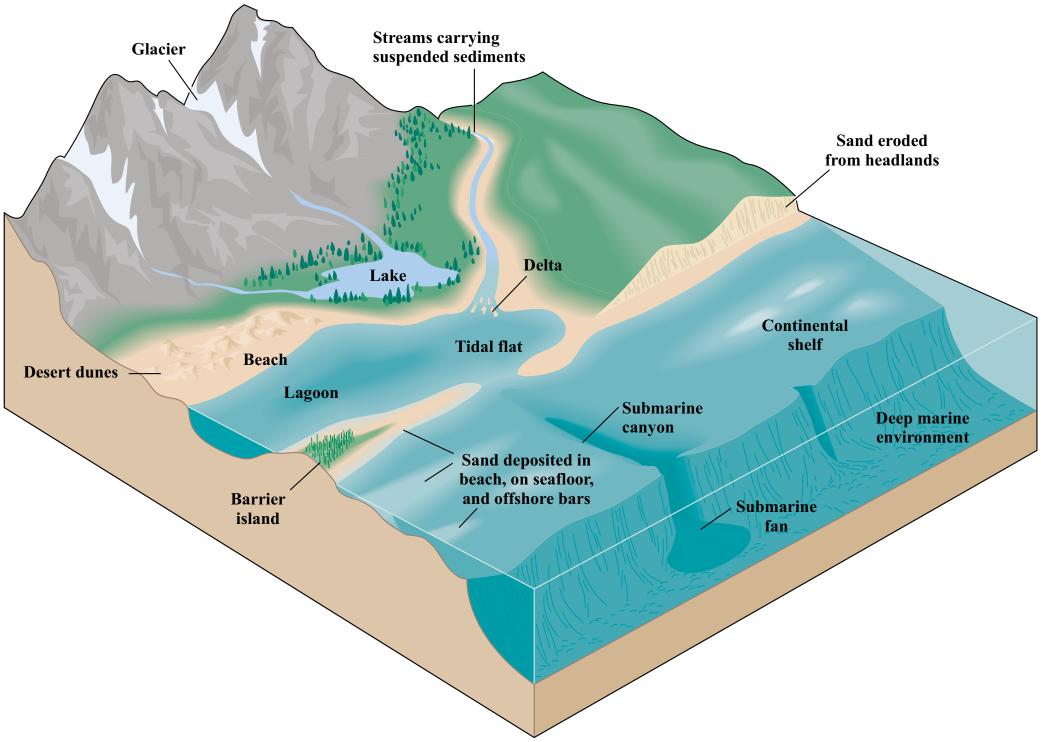


FIGURE 11-2 The major sources of sediments in the coastal ocean are erosion of the shoreline and transport of particulate matter by streams, rivers, and glaciers. Many river-borne particles are deposited in estuaries or lagoons along the coastal plain. Once in the coastal marine environment, sediment particles can be transported along the coastline and deposited on beaches, barrier islands, and offshore bars. Small sediment particles can be transported offshore by currents and deposited on the deep-ocean floor. Larger particles can be transported offshore by turbidity currents that sometimes travel down submarine canyons.

cumulate either from a local source or after being transported to the area in rivers and glaciers or by ocean **currents** and waves (Fig. 11-2). Erosional coasts are often dominated by sea cliffs and rocky shores, whereas depositional coasts include **deltas, mangrove** swamps, **salt marshes, barrier islands,** and **beach-sand dunes.**

Coasts can also be classified as either primary or secondary. Primary coasts are shaped predominantly by terrestrial processes, including erosion or deposition by rivers, streams, glaciers, volcanism, and tectonic movements. Secondary coasts are shaped by marine erosion or deposition caused by wave action, sediment transport by currents, and marine organisms (e.g., those that form reefs). Many coasts have characteristics of both marine and terrestrial processes.

Formation of Coasts

New coasts are formed either when the relative levels of the ocean surface and coastal landmass change or when the edge of the landmass is added to or removed. Some processes that form coasts, such as volcanic eruptions and earthquakes, can occur instantly or over a very short period, but most other processes, such as sea-level change and **coral reef** growth, continue slowly over centuries. Many of these processes can occur on the same coast at the same time, but at different rates or frequencies.

Tectonic Processes

Chapter 4 describes movements of **lithospheric plates** that create major **topographic** features of the ocean floor. It also explains how these movements build mountain chains and **magmatic arc** and **sedimentary arc** islands at **convergent plate boundaries**, create new oceans at **continental divergent plate boundaries,** and create volcanic islands at **hot spots** and particularly active locations on **oceanic ridges.** Tectonic processes take millions of years to re-form the planet. For example, the conversion of Pangaea to the present configuration of continents required about 150 to 200 million years.

Plate tectonic movements are slow but take place continuously, modifying coasts at plate boundaries and hot spots. At hot spots, new coast is formed when volcanoes erupt. For example, several hundred hectares were added to the island of Hawaii by an eruption of Kilauea Volcano East rift Zone that started in 1983 and continued until 2018. Kilauea **lava** from East Rift Zone eruption often flows into the sea, hardens, and extends the coastline (Fig. 11-1f). Tens of thousands of years from now a new island, Loihi, will emerge south of Hawaii (Chap. 4).

New coast is also formed by volcanic eruptions in magmatic arcs at convergent plate boundaries. Indonesia and the Aleutian Islands are good examples (Chap. 4). At convergent plate boundaries or at **transform faults**, new coast is formed when earthquakes uplift a continent edge as the oceanic plate is **subducted** beneath it, or when earthquakes uplift ocean sediments at a sedimentary arc. Although earthquakes that uplift land to create new coast are infrequent, coastal erosion processes are also slow. Therefore, new uplifted coast is formed faster at some convergent plate boundaries than it is modified by ocean processes. For example, the Loma Prieta earthquake in October 1989 raised the coastal mountains and coast near Santa Cruz, California, by as much as 1.5 to 2 m. A strong earthquake in Alaska in 1964 raised parts of the seafloor of Prince William Sound by as much as 8 m, creating a new strip of land from the former seafloor that was up to several hundred meters wide.

Coast can also be destroyed by tectonic processes. For example, coasts of what is now northern India were destroyed as India collided with Asia (Chap. 4). Earthquakes at convergent plate boundaries or at transform faults can cause sections of coastal land to move vertically downward, although such changes at these boundaries are often temporary because subsequent earthquakes may uplift this same section as the often complex subduction process continues.

Landslides

The simultaneous destruction of old coast and formation of new is particularly dramatic where volcanoes form islands, such as Hawaii, whose underwater flanks are much steeper than most other terrestrial margins. The steep flanks can become unstable as lava accumulates from continuing eruptions or when the island cools and sinks **isostatically** after moving off the hot spot. When this happens, a section of the island can break loose and slide down to the deep-ocean floor like a giant avalanche, destroying the old coast and creating a new coast where the break occurs. Huge sections of the Hawaiian Islands have apparently broken off in this way in the past. As much as 10% to 20% of Oahu apparently instantly broke loose at one time. There is evidence that about 70 more such landslides have occurred around the Hawaiian Islands during the past 20 million years. The remains of these giant landslides are littered over vast areas of seafloor extending more than 200 km around the islands (**Fig. 11-3**).

Little is known about these monster landslides or the probability of another one occurring on Hawaii or other volcanic islands. However, in November 2000 a 20-km-long by 10-km-wide section of the southeast slope of the Kilauea Volcano on Hawaii slipped about 10 cm in only 36 h, millions of times faster than most tectonic plate motions. This occurrence may have been a forewarning of an imminent (in geological time) collapse of this section of the island. Such a slide not only could destroy a large section of the islands and their inhabitants, but also could cause a huge **tsunami** (**Chap. 9**), which might be several tens of meters high when it impacted the west coast of North America. Fortunately, such large slides apparently occur only at intervals of about 100,000 years or more in Hawaii and about once in every 10,000 years on average worldwide.

Although not as dramatic in size or impact, landslides smaller than those observed around Hawaii are important processes of coastline modification on most uplifted coasts. On eroding coastlines such as those found in southern California, many homes built years ago and tens of meters from the then existing cliff edge have been destroyed as the cliffs have progressively collapsed.

Isostatic and Eustatic Sea-Level Changes

If sea level rises, coasts are drowned and a new coastline is formed inland from the previous location. Similarly, if sea level falls, ocean floor is exposed and becomes the new coast. Sea level can change on a particular section of coast because the continent edge rises or sinks isostatically (**Chap. 4**, **CC2**). Sea level can also change **eustatically** if the volume of water in the oceans changes or the volume of the ocean basins themselves changes (**CC2**). Eustatic changes take place at the same time throughout the world's oceans, whereas isostatic leveling occurs locally or regionally. At present, worldwide sea level is rising slowly because of eustatic processes (melting of glaciers and warming and expansion of ocean water), but sea level is not observed to be rising on all coasts. Some coasts are rising isostatically as fast as, or faster than, the rate of eustatic sea-level rise. The net result is that observed sea level is stable, or falling, on these coasts. Other coasts are sinking isostatically, and the observed sea level on these coasts is rising faster than the rate of eustatic sea-level rise.

Eustatic changes of sea level have made drastic changes in the location of coastlines on the continents. During approximately the past 19,000 years, sea level has risen about 120 m (**Fig. 6-17**). The history of sea-level change during this 19,000-year period can be determined by, for example, studies of the ages of **relict**

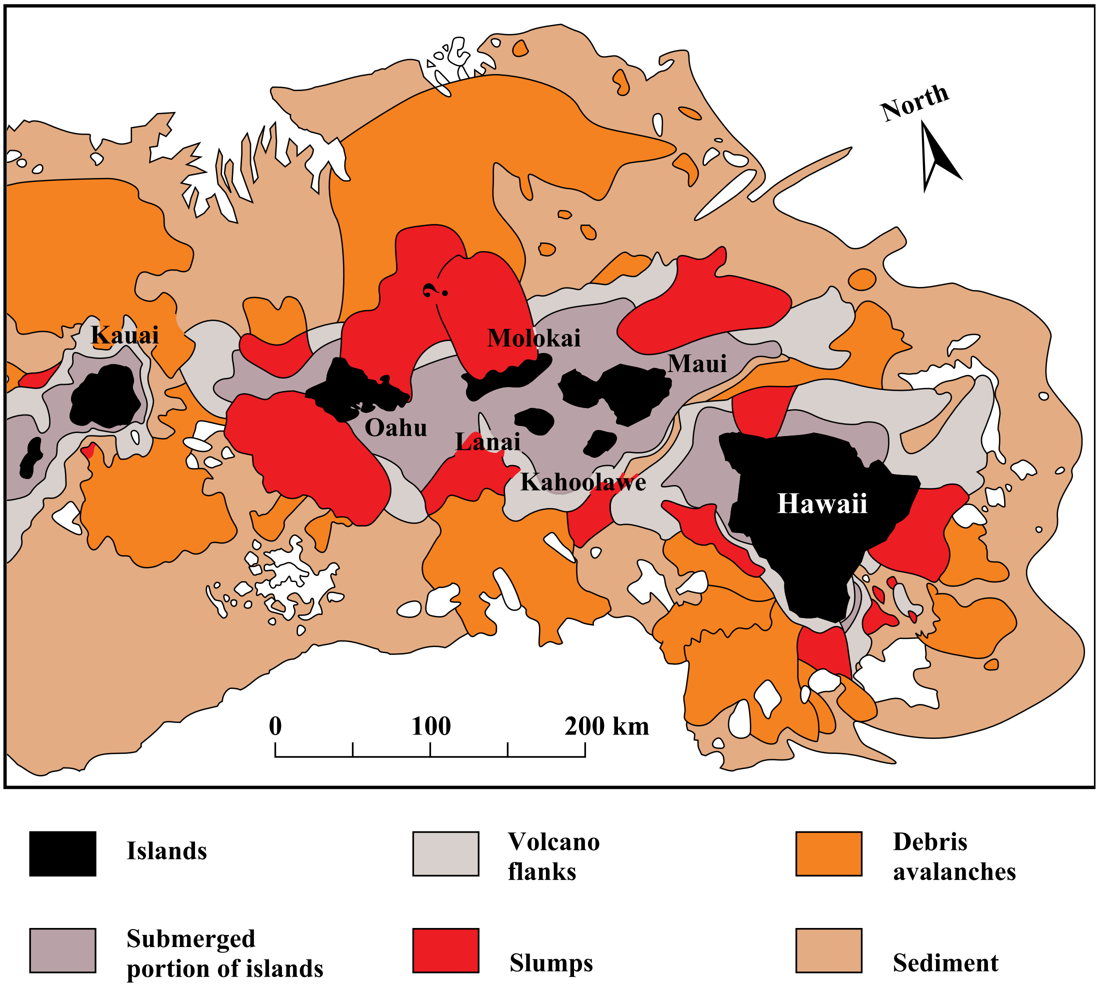
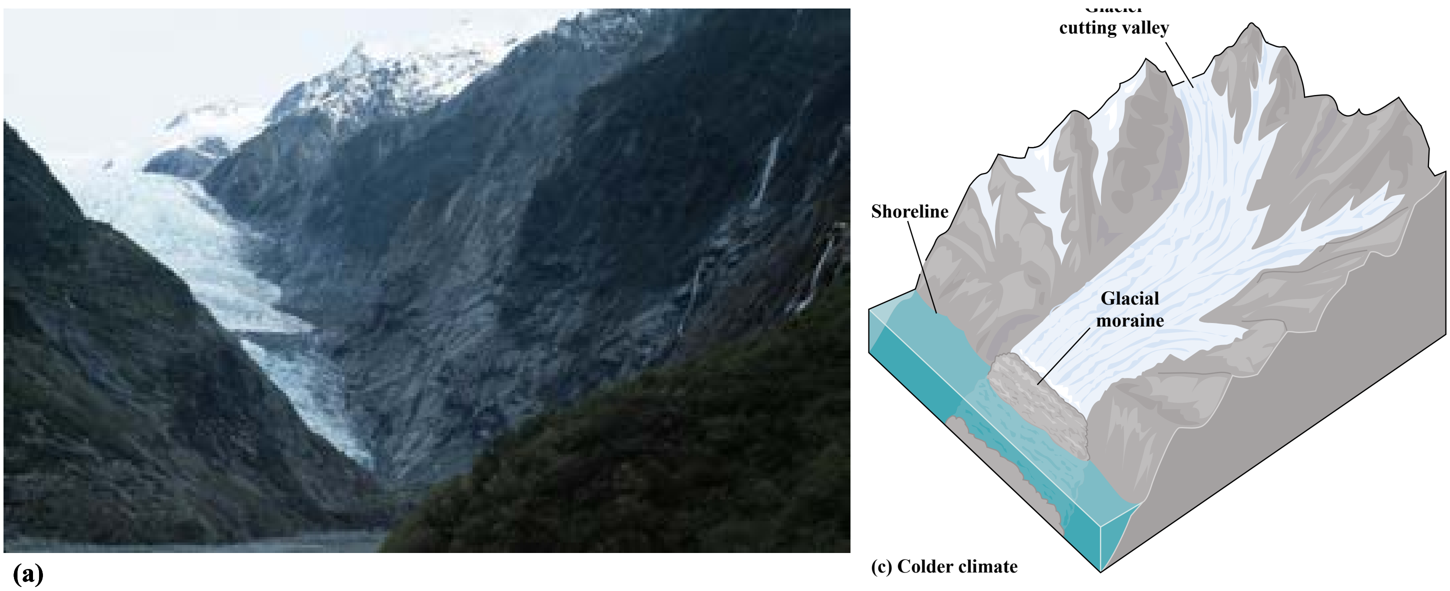
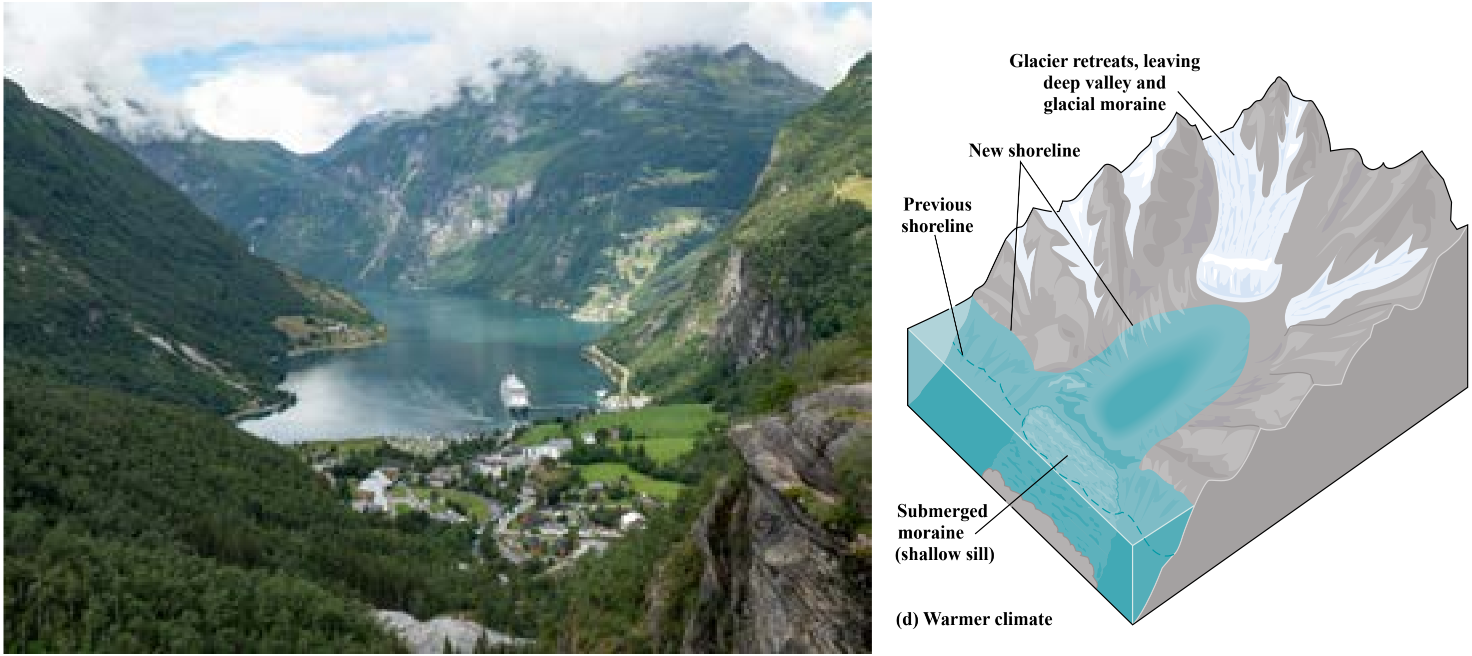


FIGURE 11-3 Large areas of the ocean floor surrounding the Hawaiian Islands are covered by slumps, fields of large debris, and sediments that originated from the islands. The data depicted on this map were obtained by the extensive use of precision sonar and three-dimensional sonar and the collection of many sediment samples. The slumps are areas where large blocks of the side of the volcano slipped downward. Slippage may occur both by a slow creeping motion and by periodic surges of several meters that cause large earthquakes. The debris fields and sediments are the result of catastrophic landslides in which huge blocks of the islands, up to 10 km or more in size, break loose instantaneously in massive avalanches that slide and flow down the steep volcano sides to the deep-sea floor. Although not recorded in recent history, these landslides must cause massive turbidity currents and, probably, massive tsunamis that may be hundreds of meters high when they reach the adjacent islands.



(a)

(c) Colder climate



(d) Warmer climate

(b)

FIGURE 11-4 Glaciers and fjord formation. (a) The Franz Josef Glacier on the South Island of New Zealand has retreated substantially in recent decades. Note the very steep-sided valley that the glacier has left behind as it has receded. (b) Geirangerfjord, Norway where rising sea level has filled a glacial valley that now allows ocean cruise ships to navigate to the head of the fjord which is 60 km inland (c)When sea level was lower and glaciers more extensive, the glaciers cut deep, steep-sided valleys down to the ancient sea level. Rock fragments carried by the glaciers were deposited to form one or more glacial moraines at the foot of each glacier. (d) As the Earth's climate warmed and sea level rose, the glaciers retreated and their steep-sided valleys were filled by seawater to form fjords. The glacial moraines left behind by the glaciers formed shallow submerged sills at the mouths of many fjords

sediments or buried sediments on the **continental shelf** (Chap. 6). Determining the history of sea level before 19,000 years ago is more difficult, but sea level seems to have oscillated many times during the present **spreading cycle**, from about 130 m or more below its present level, to about 40 to 50 m above the present level. Consider where the coastline would be if no isostatic changes had occurred during this oscillation of sea level. At the highest sea level, the Gulf of Mexico would extend across the central plains states of the United States as far north as southern Canada. At the lowest sea level, the Texas coastline would be about 150 km farther south in the present-day Gulf of Mexico and the Florida Peninsula would be about twice as wide.

During the past 4000 years, the eustatic rise in sea level has been slower than in the immediately preceding period. Therefore, most present-day coasts were formed several thousand years ago as sea level rose rapidly over what is now the continental shelf. Sea level is expected to rise more rapidly in the future as a result of global **climate** changes caused by enhancement of the **greenhouse effect**. In any event, the relatively slow sea-level change of the past 4000 years cannot continue indefinitely. If sea level does rise more quickly, the types of coasts at various locations will change because the rate of sea-level rise greatly affects the formation and migration of coastal features such as barrier islands. Coastal changes may disrupt the Earth's **ecosystems**, thereby possibly causing more damage than even that caused by the flooding of coastal cities.

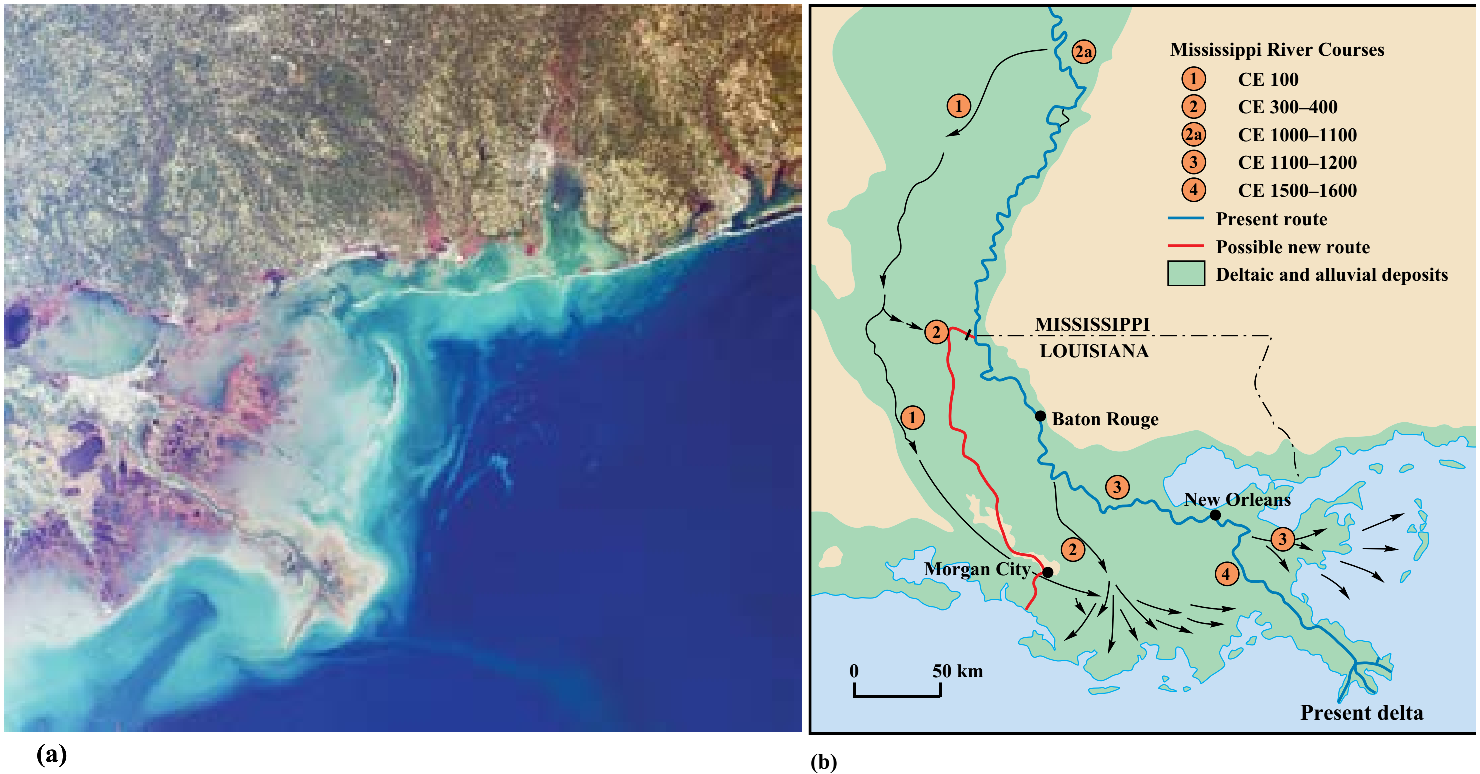


FIGURE 11-5 The Mississippi delta. (a) This satellite image shows the extensive delta with its many distributary channels. (b) The Mississippi River periodically changes its course through the coastal plain and delta, distributing its sediments across the entire area. Flood-control levees now prevent this natural process.

Because sea level is expected to rise more rapidly in response to climate change induced by the enhanced greenhouse effect, oceanographers are currently mounting intensive studies of coasts. Critical questions that remain to be answered include how fast sea level is rising eustatically and whether it will continue to rise, how isostatic changes will enhance or mitigate eustatic changes in sea level on specific coasts, and how coasts will change if the rate of eustatic sea-level rise increases.

Glaciers

As glaciers flow, they scour out steep-sided valleys (**Fig. 11-4a**). Rocks and smaller particles that have been eroded from the valley walls and floor are carried by the glacier and deposited where the ice melts at the glacier's end. During the last 19,000 years, the Earth's climate warmed and the glaciers retreated, each one leaving one or more sedimentary deposits called "moraines" at the former location of the glacier's end. At the same time, sea level was rising as ocean waters warmed and expanded, and as more water entered the oceans from melting glaciers. The rising sea inundated many steep-sided valleys cut by glaciers and created deep, narrow **fjords,** many of which are partially closed off from the ocean by a submerged **sill,** which is usually a moraine (**Fig. 11-4b,c**).

Because fjords are long narrow inlets, they are generally well protected from erosion by ocean waves, and their shores are little altered from the original sides of the glacial valley. Many high-**latitude** areas where glaciers cut through coastal mountain ranges have extensive fjord systems. Excellent examples are found on the South Island of New Zealand, in Scandinavia, on the Pacific coast of Canada and Alaska and in Patagonia, Chile.

River-Borne Sediments

New coasts are formed where large amounts of river-borne sediments are deposited. The extended delta of the Mississippi River (**Fig. 11-5**) and similar deltas elsewhere are examples of coasts formed by river-borne sediments. Deltas, discussed in more detail later in this chapter, are present at the mouths of relatively few rivers. Most of the world's rivers flow across a gradually sloping **coastal plain** before reaching the sea. The sediment load of the river is deposited in the river valley as the flow slows in this flatter area.

Only a few rivers other than the Mississippi carry such large sediment loads that their river valleys have filled enough for large quantities of sediment to be transported to the sea. Most rivers that flow across coastal plains, such as those on the Atlantic coast of North America, carry considerably less sediment than the Mississippi. In addition, rivers emptying to the Atlantic Ocean have only recently (in geological time) begun to flow toward that ocean. In the region now drained by the rivers emptying to the Atlantic Ocean, rivers flowed away from the Atlantic Ocean until about 100 million years ago, when the newly formed **passive margin** of the Atlantic coast sank isostatically sufficiently far to reverse the slope (**Chap. 4**).

Rivers that flow across tectonically active coastal margins generally flow through steep coastal mountain ranges. Because they drain relatively small land areas and flow through steep valleys to the sea, many carry relatively little sediment, but most of it is transported to the oceans. The continental shelf is steeper and narrower on these active coastal margins, so sediment carried to the ocean can be transported to the deep-sea floor more easily than at passive margins.

Biological Processes

Reef-building **corals** cannot grow and build reefs unless they are underwater. However, reefs grow fastest in shallow waters where light intensity is high (**Chap. 15**), and some reef tops emerge above water at low **tides**. Although they are not truly

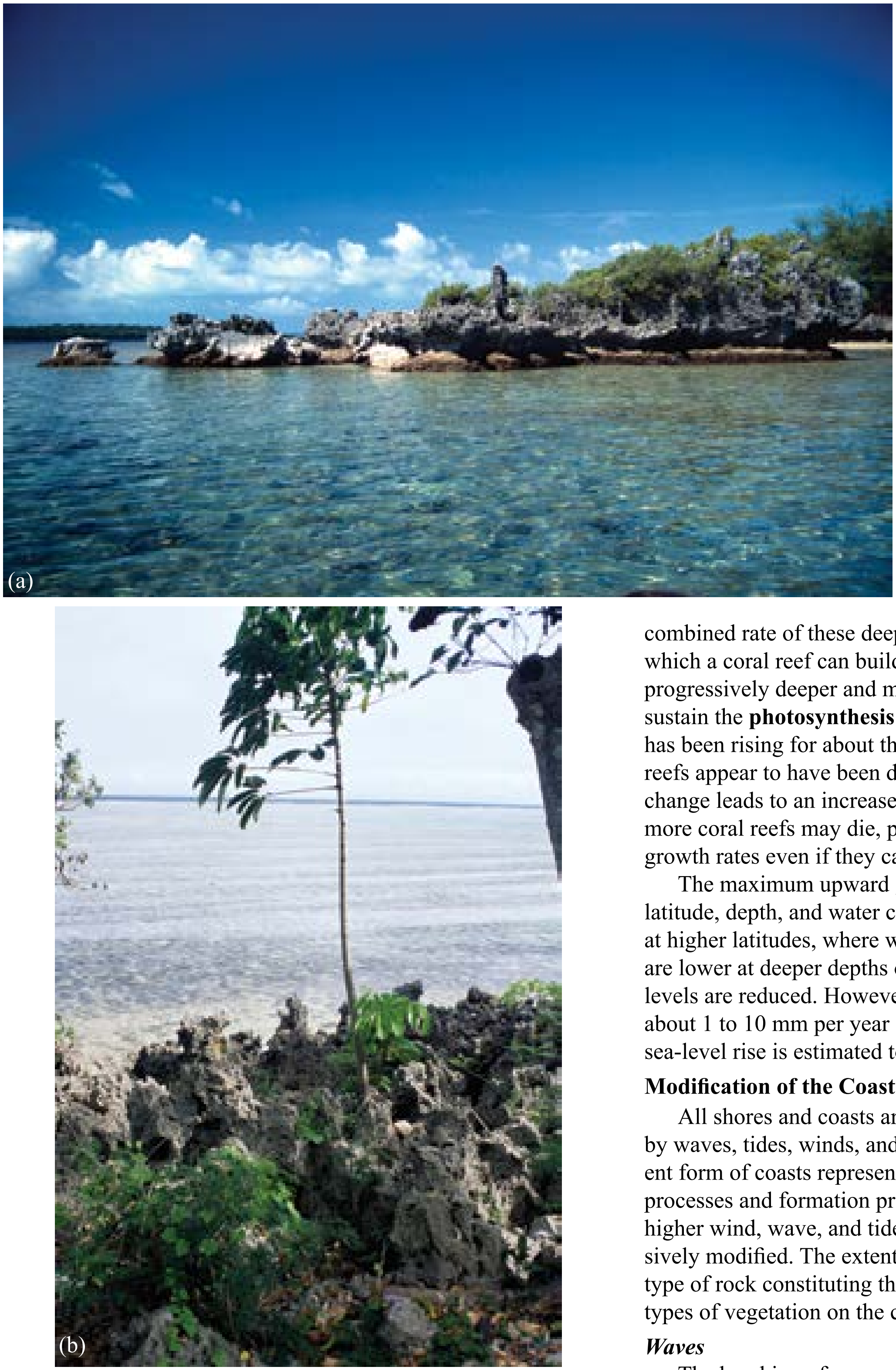


FIGURE 11-6 Uplifted and eroded coral reef forms a jagged shore often called "ironshore." (a) Coastlines of coral islands, like this island in Palau, often have interspersed sandy beaches and eroding ironshore. (b) The jagged rocks of this ironshore segment in Fiji are razor-sharp.

land, these reefs constitute an important feature of the coast because ocean waves break on them and lose much of their energy. **Fringing reefs** and **barrier reefs** are present on many coasts in tropical and subtropical regions. A small drop in sea level or a small tectonic or isostatic uplift of a coastal margin can raise coral reefs above the sea surface, where the corals cannot survive.

When corals die, they leave behind their hard "skeletons." Many tropical and subtropical islands and coasts are characterized by rocks composed of old coral reefs. These coral rock shores are eroded to form a jagged surface, often called "ironshore," that makes walking difficult (**Fig. 11-6**). The Cayman Islands in the Caribbean Sea have excellent examples of reef-dominated shore. In fact, these islands are predominantly uplifted coral reef. The ironshore on part of one island is so jagged that the local community has been named "Hell."

Many coral reefs are located on islands or submerged pinnacles that are sinking isostatically (**Fig. 4-28**). Isostatic sinking and sea-level rise both tend to increase the depth of the water column over a reef. If the combined rate of these deepening processes exceeds the rate at which a coral reef can build upward, the top of the reef becomes progressively deeper and may eventually become too deep to sustain the **photosynthesis** on which the corals depend. Sea level has been rising for about the past 19,000 years, and many coral reefs appear to have been drowned in this way. If global climate change leads to an increase in the rate of sea-level rise, many more coral reefs may die, primarily those with lower maximum growth rates even if they can survive ocean **acidification**.

The maximum upward growth rate of coral reefs varies with latitude, depth, and water clarity. Upward growth rates are lower at higher latitudes, where water temperatures are cooler; and they are lower at deeper depths or in less clear waters, where the light levels are reduced. However, the maximum upward growth rate is about 1 to 10 mm per year at 10 m depth, and the current rate of sea-level rise is estimated to be about 3-4 mm per year.

Modification of the Coast

All shores and coasts are continuously, but slowly, modified by waves, tides, winds, and biological processes. The present form of coasts represents a balance between modification processes and formation processes. Older coasts and coasts with higher wind, wave, and tide energies are generally more extensively modified. The extent of modification also depends on the type of rock constituting the coast and, in some cases, on the types of vegetation on the coastal land and in the nearshore zone.

Waves

The breaking of waves on the shore is the principal coast-modifying process. On rocky coasts, breaking waves progressively erode the rock away. Soft sedimentary rocks are eroded much faster than harder volcanic rocks. In addition, erosion is faster on coasts that are exposed to greater wave action. Wave action is greater in areas of frequent storms or where the coastline is impacted by waves that travel far across the ocean.

As discussed in Chapter 9, wave energy is focused on headlands and spreads out along the interior shores of bays. Consequently, on an indented coastline, erosion occurs fastest at headlands, and the products of erosion (sand) accumulate within the intervening bays. Preferential erosion of headlands along a coastline tends to straighten the coast progressively until no headlands remain. This process is complete on many coasts, particularly where rocks are easily eroded. The New Jersey coast is an example (**Fig. 11-7**).

On rocky coasts, waves cut away rock between the **high-**and **low-tide lines**. As rock is cut away, the land becomes unstable and breaks away, leaving behind a cliff that may be nearly vertical (**Figs. 11-1d, 11-8**). The debris from the cliff temporarily alters the shape and nature of the beach where the cliff face has collapsed. However, these rocks fall into the wave-breaking zone,

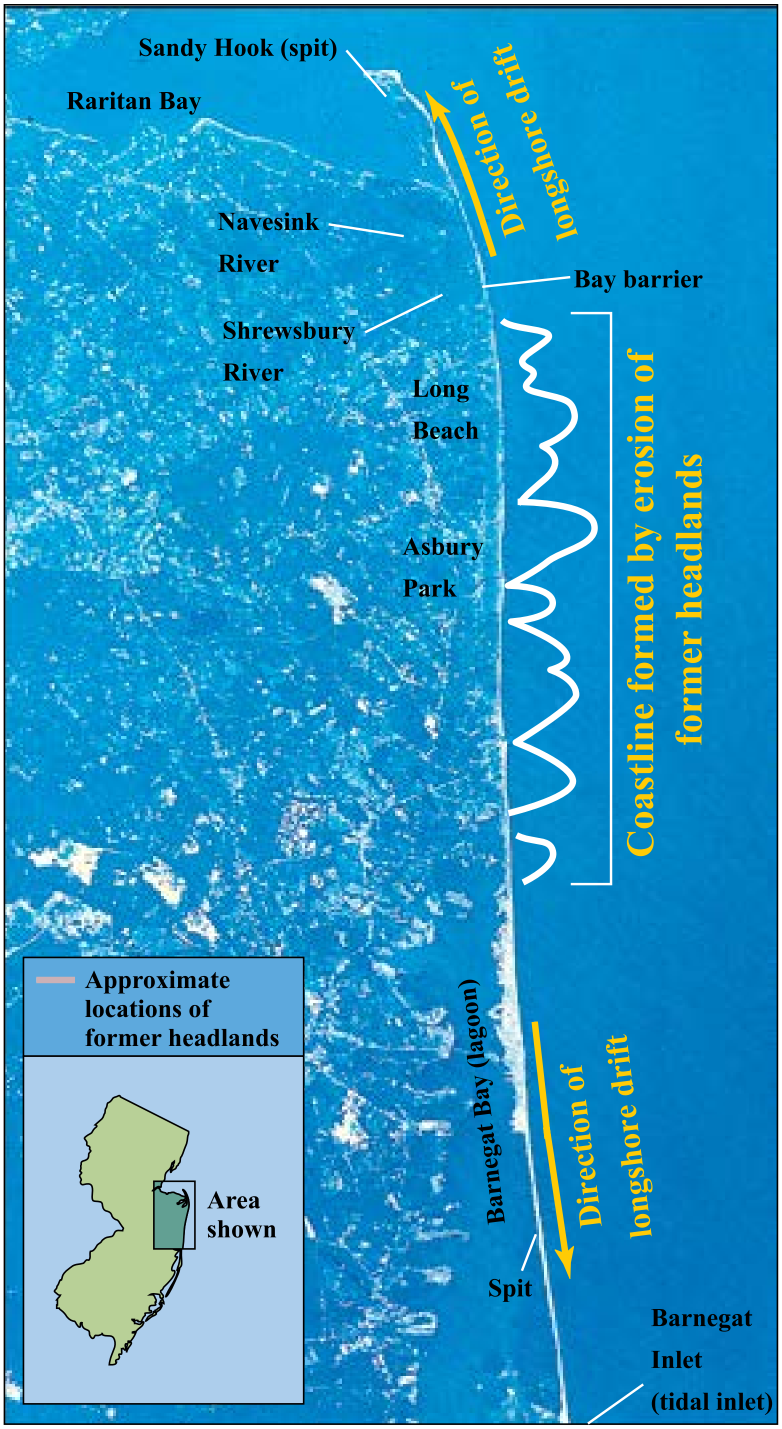


FIGURE 11-7 The New Jersey coastline has long straight beaches and barrier islands. Headlands that used to exist along the northern shore have been eroded away, providing sand for the formation and maintenance of the spits to the north and south.

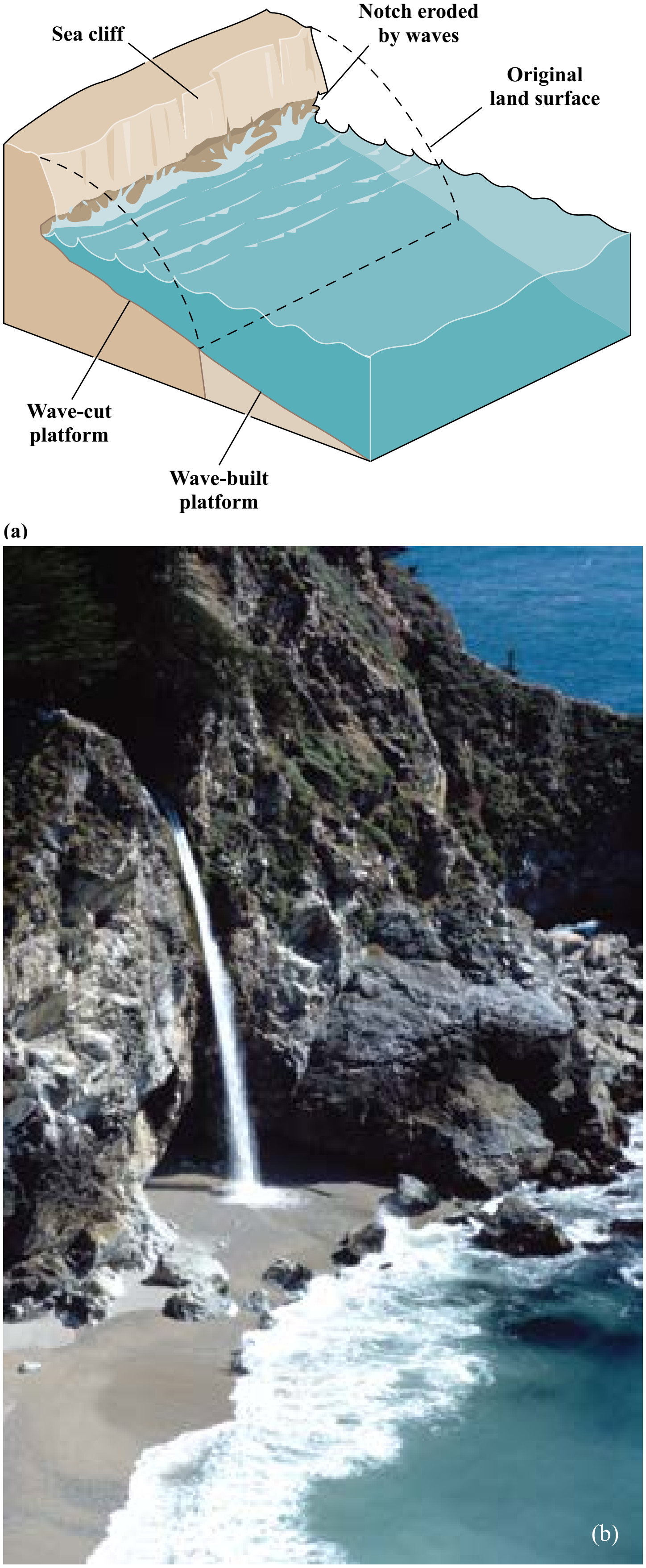


FIGURE 11-8 Wave erosion on steep coastlines can create cliffs. (a) As rock is eroded by waves, the land is undercut, becomes unstable, and slumps. The slumped material is eroded and transported away by the wave action. Thus, a gently sloping wave-cut platform is maintained at the base of the cliff. (b) Cliff and beach near Monterey, California.

FIGURE 11-9 Wave erosion, combined with boring and dissolution by marine organisms, undercut this rocky coastline on the island of Palau in the Pacific Ocean. Erosion is confined to a very narrow height range because the tidal range is nearly zero.

where they are eroded away relatively quickly. The beach is thus restored, and the waves renew their attack on the base of the cliff. In many locations, there is no beach at the base of the cliffs because wave energy is too high or wave erosion has not continued long enough for sand to accumulate (**Fig. 11-9**).

As waves cut into coastal cliffs and headlands, they encounter rocks of variable resistance to erosion. Rapid erosion of the less resistant rock often leads to the formation of sea caves at the base of a cliff (**Fig. 11-10a, b**). Sea caves that are cut into either side of a headland can continue to be eroded until they meet under what remains of the headland, resulting in the formation of a sea arch (**Fig. 11-10b,c**). As the headland erodes further, the arches collapse, and the remaining pinnacles of rock, called “stacks” (**Fig. 11-10b,d**), are eventually eroded away.

Coasts that have been substantially eroded usually have beaches. Off these coasts, waves transport and distribute particles (e.g., sand, silt, or pebbles) that make up the beach. These processes are discussed later in the chapter. Beaches help protect the coast from wave erosion.

Tides

The area along the coast that lies between the lowest point exposed at the lowest tide and the highest point reached by storm waves is the shore. The shore consists of the **foreshore**, which

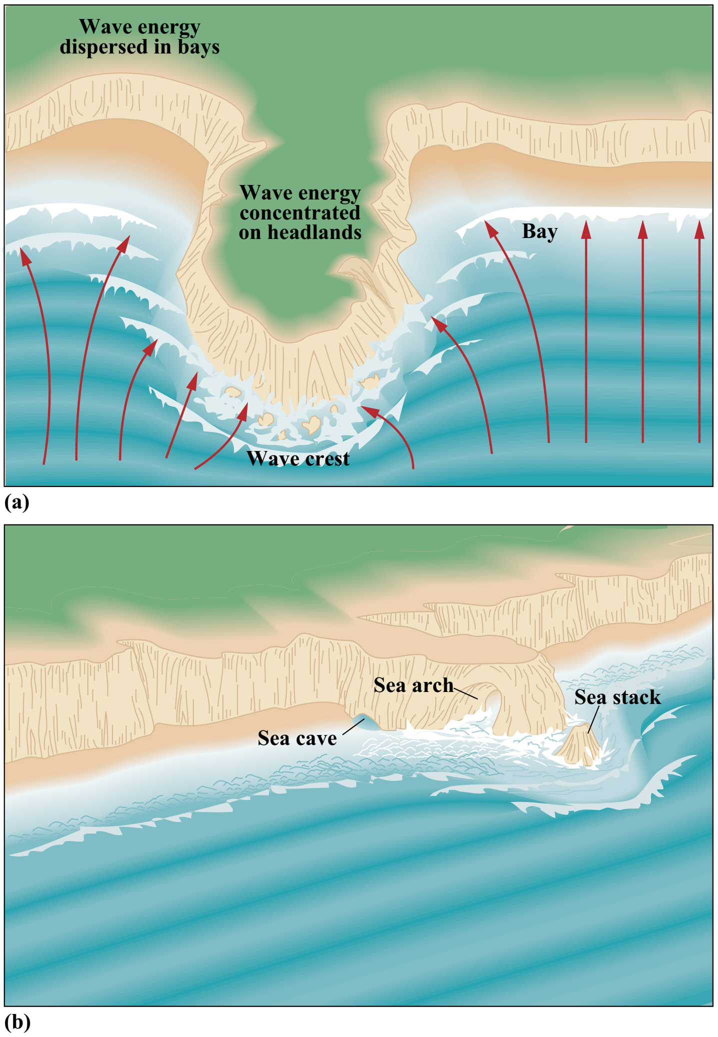


FIGURE 11-10 (a) Wave energy is concentrated on headlands by wave refraction. Because the seafloor topography is rough and varies as slumps occur from different parts of the headland, wave energy is distributed unevenly. In addition, the rocks of the headland differ in composition and susceptibility to erosion. As a result, the wave action causes the headlands to be eroded unevenly. (b) The uneven erosion of the headland can cause sea caves and sea arches to be formed. (c) This headland on the island of Molokai in Hawaii has been eroded by the intense wave action to form several sea arches and sea stacks. (d) There are many sea stacks on the Pacific coast of North America, including these on the Big Sur coast south of Monterey, California.

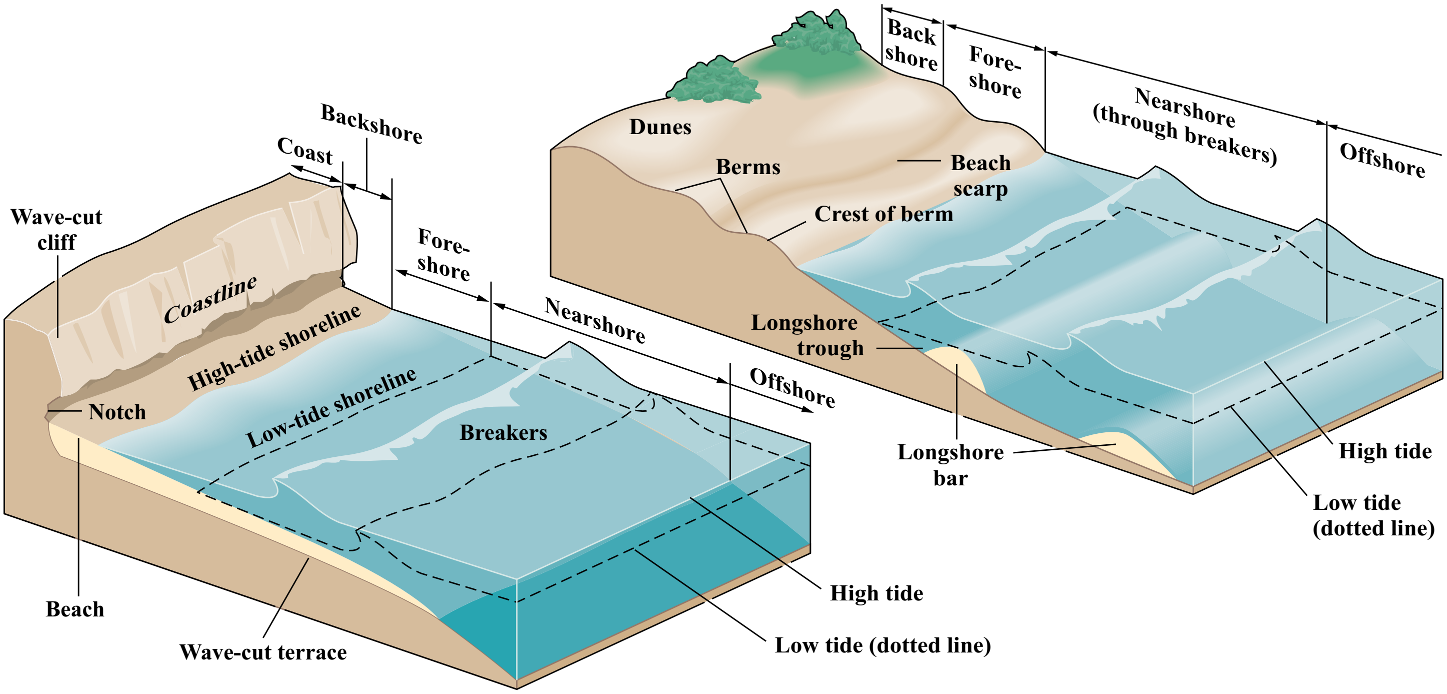


FIGURE 11-11 The coastline is separated into several zones that reflect different exposures to erosion and sediment movement due to the variation in waves and tides. The backshore is covered only in storms, but it is subject to seawater wind spray. The foreshore is the region between the high- and low-tide lines, and the nearshore is the region between the low-tide line and the depth at which wave action no longer affects the seafloor. Longshore bars and troughs may be present on the seafloor within the nearshore zone. The foreshore is often separated from the backshore by a berm. A scarp may be present in the foreshore at the height reached during a recent high tide by waves that are not strong storm waves but somewhat higher and steeper than waves that reached the beach during previous days or weeks

is the area between the low-tide line and the high-tide line, and the **backshore,** which is the area above the high-tide line that is affected by storm waves (Fig. 11-11). **Tidal range** determines the height range over which wave erosion occurs and, thus, the width of the shore. Where the tidal range is large, wave erosion energy is spread over a large vertical range. Generally, coasts with small tidal ranges are eroded faster because wave energy is concentrated in a narrow zone. The swift currents associated with large tidal ranges have little erosional effect because they are slow in relation to the orbital speed of water in waves (CC4).

Tides are particularly important in shaping and maintaining **wetlands**. Tidal motions in shallow bays and **estuaries** transport and redistribute sediments. Such areas accumulate sediments until they are filled. Extensive mudflats form just below the high-tide line and are dissected by drainage channels. During the tidal cycle, the mudflats of tidal wetlands are alternately exposed and covered by shallow water.

Winds and Weather

Onshore winds can carry sand from beaches and deposit it on the backshore above the highest point reached by waves. This process leads to the formation of the sand dunes (Fig. 11-12) that characterize many coastlines. Conversely, sand dunes and soils can be eroded by offshore winds and deposited in the oceans. Just as they are elsewhere, rocks, sand dunes, and soils of the coast are eroded by water in streams and rainfall, and by various processes, including alternate cycles of freezing and thawing and dissolution in acidic rainwater. Wind-driven particles and ocean spray may also erode rocks or soils.

Vegetation

The type and extent of vegetation on the coast affect the rate at which winds, streams, and storm waves erode the land. Grasses

FIGURE 11-12 Sand dunes are characteristic of many coasts. (a) Dunes usually separate the beach from a low marshy area, as they do on this Aruba coast. (b) Dunes can be 10 m or more high, like these in Monterey Bay, California. Note the patches of vegetation on the dunes

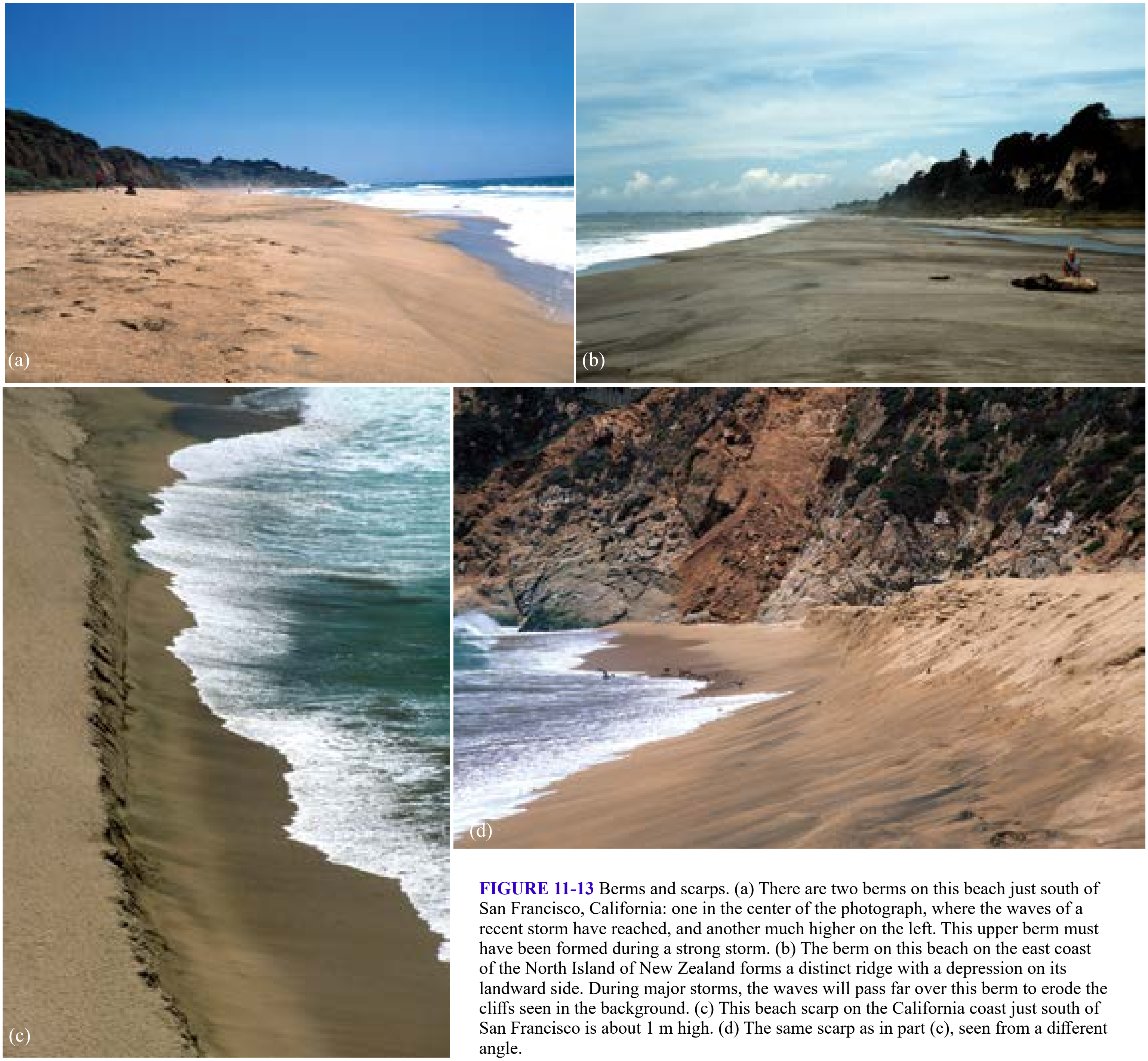


FIGURE 11-13 Berms and scarps. (a) There are two berms on this beach just south of San Francisco, California: one in the center of the photograph, where the waves of a recent storm have reached, and another much higher on the left. This upper berm must have been formed during a strong storm. (b) The berm on this beach on the east coast of the North Island of New Zealand forms a distinct ridge with a depression on its landward side. During major storms, the waves will pass far over this berm to erode the cliffs seen in the background. (c) This beach scarp on the California coast just south of San Francisco is about 1 m high. (d) The same scarp as in part (c), seen from a different angle.

are particularly important in protecting sand dunes from erosion. Similarly, rooted plants that grow in the water, including **sea grasses** and mangroves (**Chap. 15**), help prevent erosion of mudflats by waves and currents. In contrast, tree roots and animal activities, such as burrowing, contribute to the continuous erosion of rocks and soils of land near the coast just as they do elsewhere. In addition, especially on rocky coastlines, many animals that live in the zone between high and low tides erode the rocks as they bore or chemically dissolve their way into the rock or probe into cracks in the rocks, either to find food or shelter or to be able to "hold on" to the rock against the power of the waves.

BEACHES

Beaches are endlessly fascinating. We love to sunbathe on them, play in the **surf**, search for shells and other things washed up by the tide, and simply walk along them enjoying their natural splendor. To many people, beaches are the best place to enjoy what is usually an unspoiled natural **environment**. Civilizations have dramatically altered much of the dry land adjacent to the oceans, but beaches have been substantially changed in only a few locations.

Although beaches appear to be resistant to change, in reality they are places of continuous movement and transformation. Beaches are formed by processes that occur in the zone between the seaward boundary of land vegetation (or the base of a cliff, if present) and the point where the seafloor reaches a depth at which sediment is no longer disturbed by waves, commonly 10 to 20 m depth (**CC4**). This zone includes the coast and shore and is known to geological oceanographers as the **littoral zone**. Unfortunately, the term *littoral zone* means something different to biological oceanographers: the zone between the high- and low-tide lines.

The Littoral Zone

The landward side of the beach is delineated by either a cliff or sand dunes. Cliffs vary in height and steepness. Sand dunes vary from a few centimeters to more than tens of meters high and can be hundreds of meters wide. The beach that stretches out to sea from the cliffs or dunes consists of three zones. First, the backshore zone is the low-slope area of upper beach that is normally dry, even at high tide (**Fig. 11-11**). Although it is generally flat and slopes only gradually downward toward the sea, the backshore may have well-defined areas where the downward slope steepens abruptly (**Fig. 11-11**). Such areas are called **berms**. The top of a berm, built by sand deposited on the beach during periods of quiet wave action, is usually flat, and the seaward side slopes downward relatively steeply (**Fig. 11-13a**). Sometimes the berm appears as a slight mound or ridge (**Fig. 11-13b**). Berms generally continue along the length of the beach at a fixed height above the water. In many places, we see several berms on the same beach at different heights above the water.

Berms are created by storm waves that cut away sand to form the steeply sloping side of the berm. The highest berms are created by storm waves that reach farthest up the beach. Because the strongest storms occur in winter in most locations, the uppermost berm is often called the “winter berm,” even though it may actually have been created by an infrequent great storm that occurred one or more years earlier. Berms are not permanent features. They are continuously destroyed and new ones are formed as **wave heights** and tidal ranges vary. Where there is more than one berm on a beach, the uppermost berm must have been formed first, followed in succession by each lower berm, as storms will obliterate any berm that is lower than the height on the beach to which its waves reach.

The second zone of the beach is the foreshore (**Fig. 11-11**). It is the area between the highest point reached by waves at high tide and the lowest point exposed at low tide. This area is commonly an almost flat and featureless slope and is often called the **low-tide terrace**. Foreshore slopes can vary greatly from beach to beach and from month to month at the same beach, but they are generally greatest on beaches composed of coarse grained material. At the landward edge of the low-tide terrace (the high-tide line), There is often an abrupt vertical face of sand, usually a few centimeters high, before the beach slopes normally upward again as dry backshore. This feature is called a **scarp** (**Fig. 11-13c, d**). Like a berm, a scarp stretches along the beach, and there may be more than one. Scarps are caused by waves that are somewhat stronger than those that have reached the beach in previous days or weeks cutting away sand from the beach, and the location of the scarp represents the height that these waves reach at high tide. Waves flatten the low-tide terrace when it is covered with water.

If two scarps are present, the one higher on the beach was formed before the lower one at a time when either the tide (**spring tide**), waves, or both were higher. The lower scarp would have been flattened and destroyed if waves had passed over it to cut the higher scarp. The boundary between backshore and foreshore is defined as the location reached by waves at high tide. This location is not fixed, because the maximum tidal height changes from day to day (**Chap. 10**) and wave action varies. When waves are small, they do not reach far up the beach. However, storm waves can crash far beyond the highest point reached by smaller waves. In addition, when strong coastal winds blow, **Ekman transport** can raise or lower sea level on a coast by a meter or more (**Chap. 8**).

Seaward of the low-tide line, the beach continues to slope downward. However, if we were able to remove the water, we would see, at some distance offshore, a trough parallel to the beach. Seaward of the trough there is a rounded, elongated mound of sand, called a **longshore bar**, before the seafloor resumes its downward slope (**Fig. 11-11**). Sometimes there is more than one longshore bar, each located at a different depth and distance from shore. Longshore bars are created and maintained by wave-driven sand movement. Although we cannot see submerged longshore bars, we may see evidence of them. When high waves with a long **wave period** approach the shore, a line of surf generally forms tens or hundreds of meters offshore. The offshore surf line is caused by a longshore bar or reef where the seafloor is elevated and water is shallower than it is immediately inshore or offshore. Waves may break over this bar (**Chap. 9**), then re-form over the deeper water inshore and break again near the beach.

In some areas, longshore bars have been built up high enough to emerge above the normal water line and become barrier beaches or even barrier islands. Longshore bars and barrier islands are dynamic features that are continuously created, destroyed, and moved. Some consequences that often ensue when we ignore this basic truth are discussed later in this chapter.

Sources of Beach Materials

For most of us, the word *beach* conjures up visions of a long strip of land next to the water that is composed of sand grains. The grains and beach usually have a color so familiar that it is called “sandy.” However, not all beaches are composed of the familiar sandy materials. Some are composed of rounded pebbles or cobbles (**Fig. 11-14a**), and the color of the sand on a beach can vary dramatically.

For example, volcanic island shores where the coast consists of recently solidified black **basaltic** rocks have black sand beaches (**Fig. 11-14b**). The island of Hawaii has several black sand beaches. Other beaches on Hawaii and Maui consist of green or red sand, where the coasts consist of volcanic ash with high concentrations of iron or other elements that form colored minerals. In some cases, these odd-colored Hawaiian beaches are only a few hundred meters around a headland from beaches that have a more typical sandy color. The sand grains on such beaches obviously originate from erosion of local rocks. Erosion is continuous on all shores and is due primarily to the action of waves.

When rocks are **weathered,** some minerals slowly dissolve and others change in composition. After prolonged exposure and erosion, only the most resistant minerals remain. The most resistant rocks include granite, which is composed mostly of the solution-resistant silicate minerals, primarily quartz and feldspars. Beaches on many shores consist mainly of grains of these minerals that, with their impurities, have the common sandy color. Sand grains on such beaches have been subjected to long exposure to water and may have been eroded upland and brought to the beach by rivers.

Many low-lying coasts have no rivers that can carry large amounts of quartz and other mineral sand grains to the ocean and have little coastal erosion. Beaches in such areas are absent or poorly developed and may be composed of other materials. In many tropical or subtropical areas, particularly on low-lying coasts, beaches are composed primarily of calcium carbonate

FIGURE 11-14 Many beaches are not soft and sand-colored like those that are so popular for recreation. (a) This beach in New England is covered by large cobble-sized deposits, a sure sign that intense storm waves often reach this beach and transport all of the fine-grained material elsewhere. (b) The sand on this beach on the south shore of the island of Hawaii is black. The sand particles that make up the beach are eroded from nearby black volcanic rocks. Unfortunately, the beach shown here has now been destroyed by lava flowing from the Kilauea volcano.

in the form of shell fragments from **foraminifera, mollusks, echinoderms,** and of platelets from **calcareous algae** such as *Penicillus* sp. and *Halimeda* sp.

If we look carefully at a handful of sand, we see that its grains consist of several materials. Sand is a mixture of particles from different sources. Sand composition may differ on two beaches that are close to each other, indicating that local river input, local erosion, or shell fragment washup contributes most of the material on at least one of the beaches. However, along most coasts, sand has much the same composition on all the beaches between any two river mouths, aside from some variations in **grain size.** On these coasts, river transport may be the dominant source of beach sands, and coastal erosion may be less important. However, for many locations the relative contribution of each source is not well known. If rivers supply most of the sand for beaches stretched out along many kilometers between river mouths, sand must move along the coast from the river mouths to form the beaches. This movement is achieved by **longshore drift.**

Longshore Drift

As waves travel through shallow water, some of their energy is transferred to sand grains, which sets them in motion (**CC4**). This interaction continuously forms and re-forms beaches and transports sand along the coast.

When a wave breaks, it rarely does so exactly parallel to the **shoreline.** Usually the wave approaches from a slight angle (**Chap. 11**), and the water that crashes on a beach does not move directly up the beach slope (**Fig. 11-15**). As the breaking wave moves up the beach (the **swash**), it **resuspends** sand grains from the beach and carries them with it. Thus, sand grains move up the beach, and a small distance downcoast, in the direction of the waves. When the water from the broken wave flows back down the beach (the **backwash**), sand grains flow with **gravity** directly down the beach slope (**Fig. 11-15**). Each swash and backwash cycle may move the grain only a centimeter or two along the beach. The net result is that sand grains are carried along the beach in the direction of the waves by a series of saw-toothed

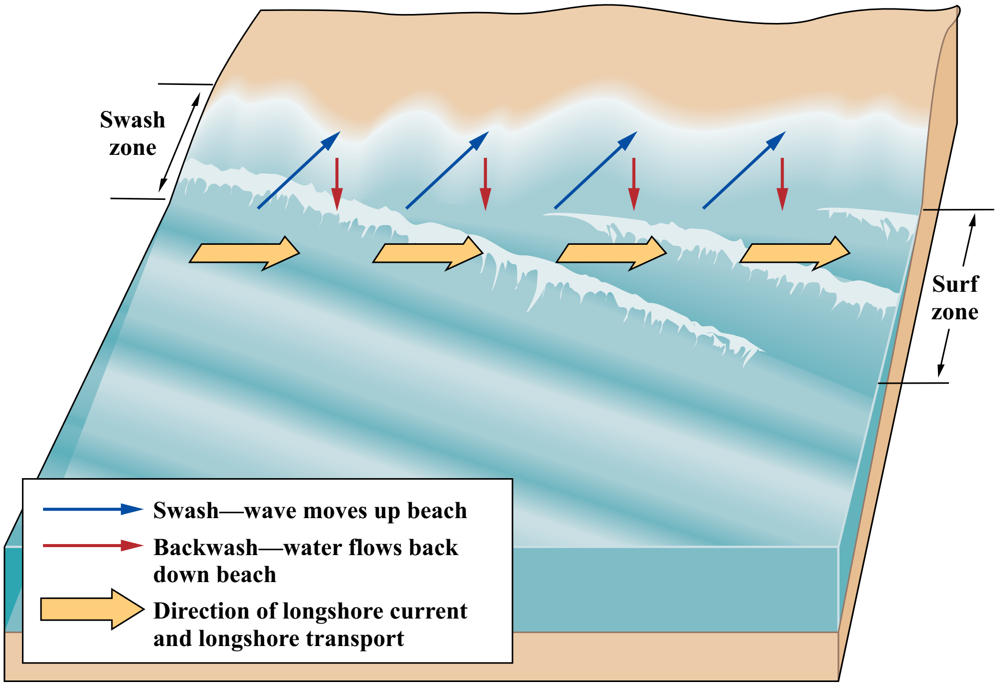


FIGURE 11-15 Water moves up a beach face at an angle with the wave direction but returns directly down the beach slope. Sand picked up by the incoming wave is washed up the beach and is returned seaward a small distance further down the beach in the direction of the waves. Successive waves move sand progressively along the beach—a process known as “longshore drift” or “littoral drift.”

FIGURE 11-16 There are several north-to-south littoral drift cells in southern California. Each of these cells ends at the head of a submarine canyon where the sand is lost as it is transported down the canyon.

swash and backwash movements. Water from the wave is also transported along the beach, creating a **longshore current** in the zone landward of the breakers. Movement of the sand with this current is called **longshore drift** or **littoral drift.**

Although each wave moves sand grains only a very small distance along the beach, waves follow each other every few seconds in a continuous series. As a result, sand can be moved by longshore drift at speeds that range from the typical rate of a few meters per day to as fast as 1 km per day. Large quantities of sand are moved along the coast by longshore drift. Transport along the east and west coasts of the United States is estimated to range from several hundred to more than 5000 m^3 of sand per day, depending on factors such as the height and **frequency** of waves.

Longshore drift is directed downcoast, in the direction away from which the waves approach, and it can reverse if that direction changes. Waves on both the east and west coasts of the continental United States, particularly the larger and more energetic storm waves, come predominantly from the north. Therefore, longshore drift is generally to the south along both coasts.

If so much sand moves along the coast every day, where does it go and why is there any sand left on the beaches? As sand moves along the coast, it may eventually meet the head of a **submarine canyon**. Instead of continuing to move along the coast, it is funneled into the canyon and flows down onto the deep-sea floor. As this sand is lost, new sand is brought to the beach by river flow and erosion of the shore. The beach is maintained by the balance between sand supplied from these sources and sand lost down the canyon. Thus, along the coast there is a series of separate cells within which beach sand is supplied and transported until it meets the head of a submarine canyon. Southern California has four well-defined coastal cells of this type (**Fig. 11-16**). Little or no sand passes south from one cell to the next. If you drive down the California coast, you can see the southern ends of these longshore drift cells where the sand beach ends abruptly. You see cliffs or cobble beaches as you continue south from these points until you reach an area sufficiently supplied with new sand to form the first beach of the next cell.

The future of California's beaches is in some doubt. Most rivers emptying into the Pacific Ocean have been dammed. Each dam acts as a trap for sand moving down the river. In addition, the dams and water withdrawals reduce the rivers' flow rate and speed, thereby reducing their ability to erode rocks and to carry sand (**CC4**). If rivers, rather than coastal erosion, are the major historical sources of most sand on California's beaches, this reduction in river flows will lead, or may already have led, to the progressive depletion of sand on the beaches. Beaches will, or may already have, become narrower, and waves will, or may have been able to,more easily reach the backshore, where communities such as Malibu are already susceptible to wave damage. Loss of river borne sand may be compensated by an increase of sand derived from coastal erosion, which is increasing due to climate change driven increase in wave energy and rising sea level. Sand supply by rivers and by coastal erosion are both highly variable and, as discussed later in this section, sand is also continuously moved between beaches and offshore bars. Because of this variability studies of the future fate of, and the existing effects of dams on, these beaches have been inconclusive. However, many California beaches have required regular beach nourishment (placement of new sand by humans) since the 1930s.

Longshore drift cells on many other coasts are not as well defined as those on the California coast. For example, on the North Atlantic coast of the United States, the cells are irregular and complex because of the many local barriers to longshore drift, such as headlands, deep river mouths, and rocky shores. In addition, this coast has a broad, flat continental shelf and few steep canyons through which sand can be transported offshore.

Wave Sorting of Beach Sands

Waves move sand if the speed of orbital motion is fast enough to resuspend the sand grains (**CC4**). Water in the wave moves toward the beach with the wave **crest** and then away from the beach when the **trough** passes over. Therefore, we might expect resuspended sand grains to move forward and back and return to their original location with each wave pass. However, the **orbital velocity** of the wave is distorted by its interaction with

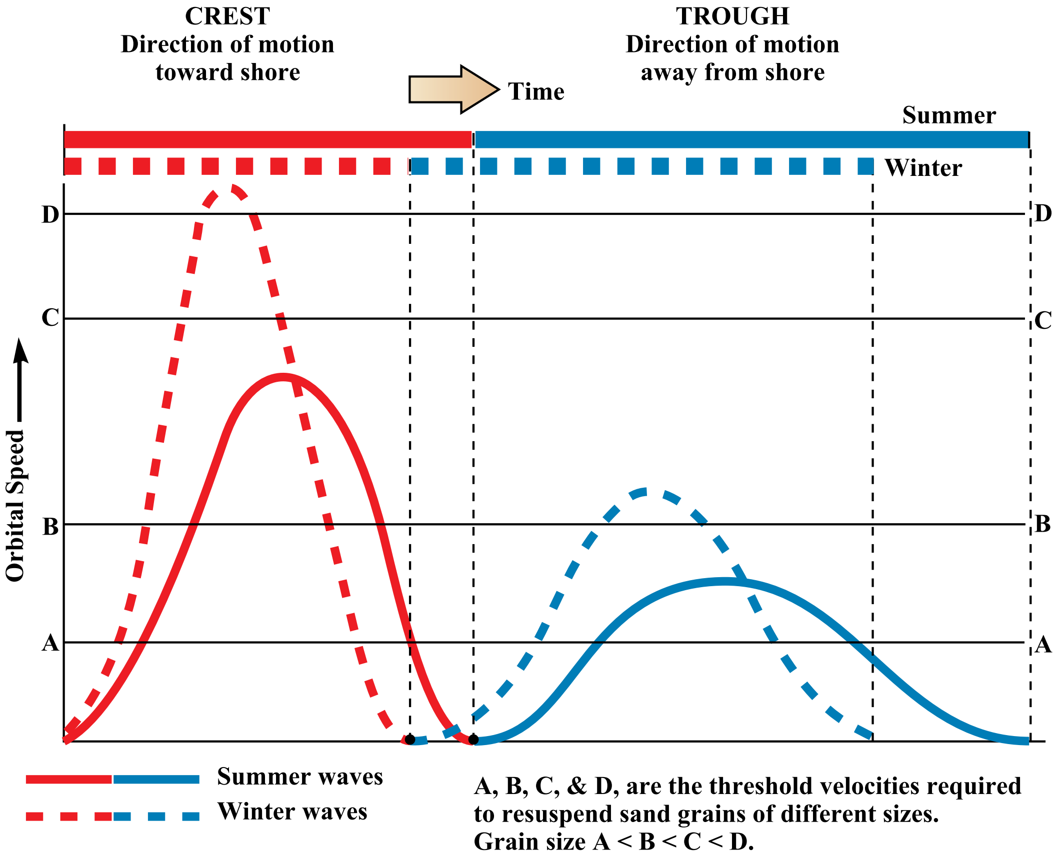


FIGURE 11-17 Water in a wave moves onshore with the crest at higher speeds and for a shorter period than it moves offshore with the trough. Winter waves generally have shorter wavelengths, greater wave heights, and thus, faster orbital speeds than summer waves. The text describes how variations in wave orbital velocities affect the transport of different sizes of sand grains (A, B, C, D) on a beach and how these processes sort sand grains by size.

the seafloor. Water particles are farther from the seafloor as they flow toward the beach in the wave crest than they are as they flow back away from the beach in the trough. Because bottom **friction** increases nearer the seafloor, orbital velocity is lower in the wave as water moves offshore (trough) than it is when the wave moves onshore (crest). Although offshore (trough) flow is slower, it lasts longer than onshore (crest) flow. If this were not so, the wave orbit would not be complete (Fig. 11-17).

The responses of sand grains to the difference in orbital velocity between crest and trough and to the varying height and **wavelength** of waves reaching the beach are the factors that control the movement of sand grains across the littoral zone. Winter storm waves are generally higher than summer waves, and they have shorter wavelengths and periods. The orbits are larger (higher waves) and must be completed in less time (shorter period) in winter waves, so they have higher orbital velocity.

Consider the movements of sand grains of different sizes in response to winter and summer waves. In Figure 11-17, sand grains of size A are small enough to be resuspended easily by passage of both the crest and the trough of winter and summer waves. Even if there is time for such grains to be deposited temporarily between crest and trough, they are immediately resuspended and will not be deposited on the beach. These particles eventually are carried offshore by **rip currents**. Once in deeper water, they settle to the seafloor, where waves will no longer resuspend them, because the orbital velocity of waves in deeper water is reduced with depth below the surface (Chap. 9). Thus, fine-grained sand is winnowed from the beach, transported seaward, and deposited in deeper water below the influence of waves. The finest-grained sand is resuspended and transported offshore, where it is carried by ocean currents until deposited elsewhere (Chap. 6).

Sand grains of size B (Fig. 11-17) are resuspended under the crest of summer waves, but they cannot be resuspended by the slower orbital velocity under the trough. These particles are resuspended, moved shoreward with the crest, and redeposited as the velocity drops. They remain in place through the return flow (trough), which has lower velocity, and are resuspended and moved farther shoreward by the next crest. Thus, summer waves move sand grains of this size range from offshore onto the beach. When larger winter waves arrive, size-B grains are resuspended under both crest and trough and therefore are moved offshore. Because size-B grains are relatively large, they are not transported by ocean currents (whose velocities rarely approach the orbital velocities of waves), so they are deposited offshore just beyond the depth of wave influence. Hence, during winter, size-B particles are removed from the foreshore, transported offshore, and deposited to form a longshore bar. The longshore bar builds until it is just deep enough that the orbital velocity of passing waves is not quite fast enough to resuspend the sand grains.

Larger sand grains, of size C (Fig. 11-17), are moved up the beach by strong winter waves, but they are too large to be moved back offshore, even by the most intense storms. The largest grains (size D) cannot be moved at all and will remain until they are eroded or physically broken down into smaller grains that can be moved.

If wave action were the only process occurring, we would expect beaches to be composed of a mixture of sand grains of different sizes, lacking only those small enough to be continuously resuspended and removed to the deeper ocean. Beaches protected from strong wave action would be an unsorted mixture ranging from fine-grained sand to pebbles and boulders. Beaches with greater wave action would have no sand grains below a certain size. This grain size minimum would be larger for beaches subjected to strong wave action, but all grain sizes above the minimum would be present. However, we rarely find such a mixture. Each beach tends to be characterized by a narrow range of grain sizes, although the range varies from beach to beach (e.g., Fig. 11-14).

Why are virtually no large grains found on a fine-sand beach and no pebbles found on a sandy beach? The answer is that the range of grain sizes present depends on the sediment supply as well as on wave energy. The sand that makes up a beach is supplied mainly by river inflow or erosion of rocky headlands and is carried to the beach by longshore drift. Large particles, such as those of size D in **Figure 11-17**, cannot be transported, because they cannot be resuspended and moved by longshore drift, even by the most intense waves. Therefore, any boulders and other large particles present on a beach must have been eroded from the adjacent cliffs.

The size range of beach sand particles is thus limited because particles must be small enough to be resuspended and moved by longshore drift, but large enough not to be resuspended easily by the troughs of the waves. This explains why we normally see only a narrow range of grain sizes among particles on most beaches. Sedimentary deposits are said to be well **sorted** when they have only a narrow range of grain sizes (**Chap. 6**, **CC4**). Beaches with extremely fine sand are those best protected from wave action (and any coarser material present is rapidly buried). Pebble or cobble beaches, such as that shown in **Figure 11-14a**, are regularly exposed to intense storm waves that winnow away smaller particles.

Seasonal Changes in Beach Profiles

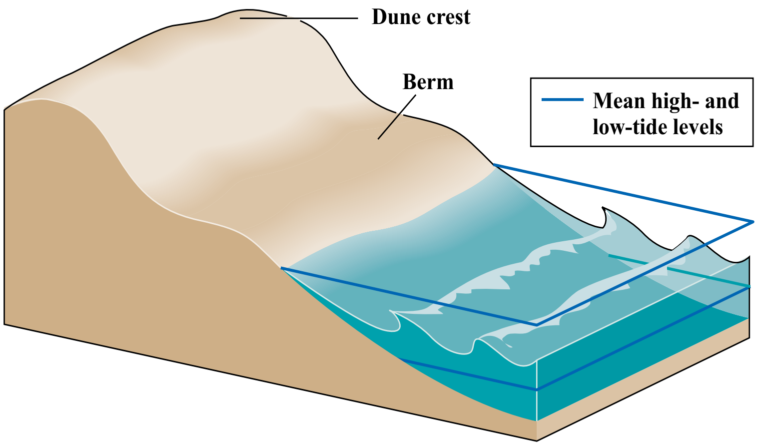
If we look carefully, we can see that the sand of beaches with calm summers and stormy winters is finer-grained in summer than in winter. In winter, large and small sand grains are transported along the beach by longshore drift, but the finer grains are also moved offshore and deposited as longshore bars. In summer, these finer grains are moved back onto the foreshore, where they cover or mix with the coarser grains of the winter beach.

Seasonal movement of sand changes the beach profile. In winter, the foreshore moves back toward the cliffs or dunes as sand is winnowed by winter waves and deposited offshore. The foreshore is more gently sloped in winter than in summer, but the backshore is steeper (**Fig. 11-18**). When "quiet" conditions of summer return, fine-grained sand is returned to the beach from offshore. However, the summer waves do not reach as far as the winter waves, so a rounded ridge of sand may be formed at the highest point that these summer waves reach (**Fig. 11-18a**). This beach ridge, or crest, is a summer berm. When a summer storm temporarily increases wave energy on a steep summer beach, the beach below the berm can be cut away temporarily to form a scarp (**Fig. 11-13c, d**). In most cases, the scarp dries and is flattened by **slumping** and winds, or is destroyed by waves of subsequent storms.

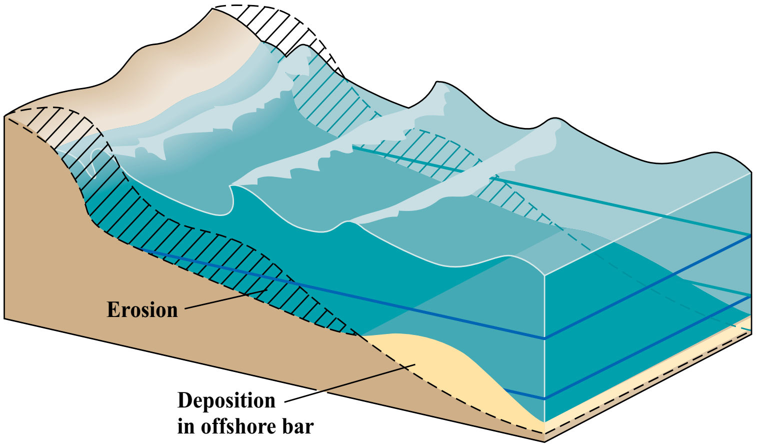
Reconfiguration of the beach and winter removal of its sand to longshore bars is an important process that protects the coast from erosion by the huge waves generated by exceptionally large storms. Longshore bars are built by shorter-wavelength waves from the less intense storms that characterize most of the winter. Therefore, they are shallow enough to cause the exceptional huge waves to break. Wave energy is partially dissipated as the wave breaks over the longshore bar, and the weakened wave causes less damage when it hits the shore. Some of the consequences of ignoring the protective nature of longshore bars are discussed later in this chapter.

Beach Slope and Grain Size

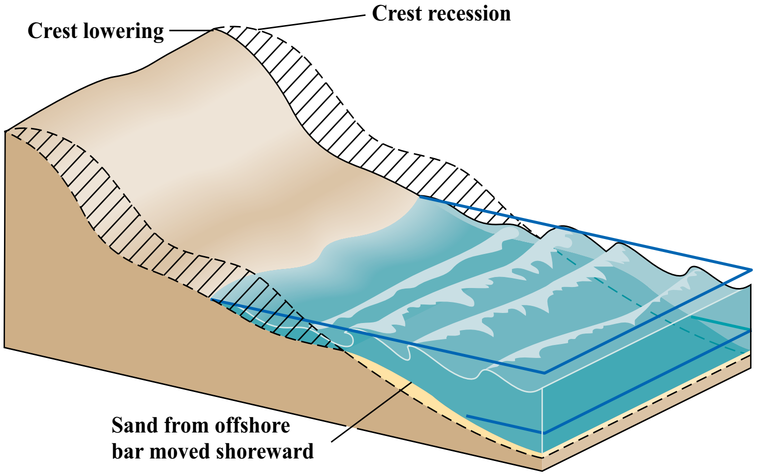
Beach slope between high- and low-tide lines depends not only on wave size, but also on the grain size of beach materials. Pebble and cobble beaches can have slopes of 10° to 20°, whereas the finest sand beaches have slopes of 1° or less. The slope reflects the conditions needed for the equilibrium of particle



(a) Summer profile



(b) Winter profile



(c) Beach returns to summer profile when wave energy is decreased

FIGURE 11-18 Seasonal variation in beach profile. (a) During summer, when waves are relatively gentle, the beach profile is steep, and one or more summer berms form immediately above the high-tide line. (b) Winter or storm waves, especially when combined with storm surges, reach farther up the beach and erode sand from the berm, moving the sand seaward to form one or more offshore bars. The result is a narrower flat-beach foreshore that is cut back to dunes or a winter berm left from periodic extreme winter storms. (c) When storm waves cease, the gentler waves return sand from the offshore bar to the beach, rebuilding its summer profile. If storms are strong in a particular winter, the beach may recede inland, and dunes may be somewhat lowered

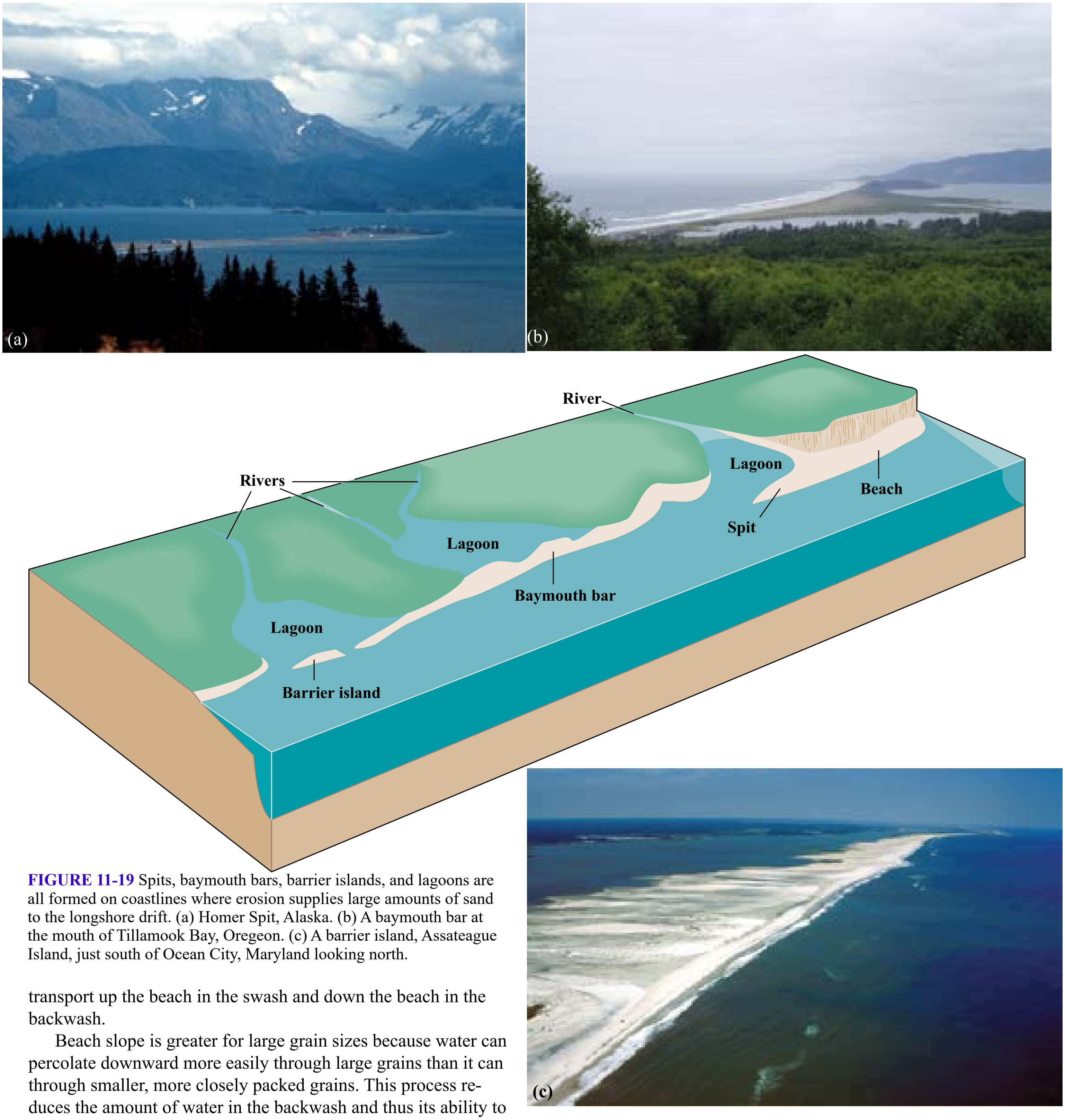


FIGURE 11-19 Spits, baymouth bars, barrier islands, and lagoons are all formed on coastlines where erosion supplies large amounts of sand to the longshore drift. (a) Homer Spit, Alaska. (b) A baymouth bar at the mouth of Tillamook Bay, Oregeon. (c) A barrier island, Assateague Island, just south of Ocean City, Maryland looking north.

transport up the beach in the swash and down the beach in the backwash.

Beach slope is greater for large grain sizes because water can percolate downward more easily through large grains than it can through smaller, more closely packed grains. This process reduces the amount of water in the backwash and thus its ability to carry particles seaward. Consequently, sediment moves onshore and builds the beach slope. The slope increases until the backwash is strong enough to move particles down the beach as fast as they are moved up.

BARRIER ISLANDS AND LAGOONS

Many coasts, including large stretches of the Atlantic Ocean, Gulf of Mexico, and Beaufort Sea (Alaskan Arctic) coasts of the United States, have low, elongated sandy islands offshore from the mainland coast (**Figs. 11-1, 11-19**). These islands are aligned approximately parallel to the coast and are called "barrier islands." Landward of the barrier island, there is usually a calm shallow **lagoon** in which sea grasses, mangroves, or marsh grasses may grow. Barrier islands and their sheltered lagoons are important because they protect the coast from erosion caused by storm waves. In addition, the sheltered lagoons provide **habitat** for the juveniles of many marine **species**.

Formation of Barrier Islands

The mechanisms that lead to the formation and migration of

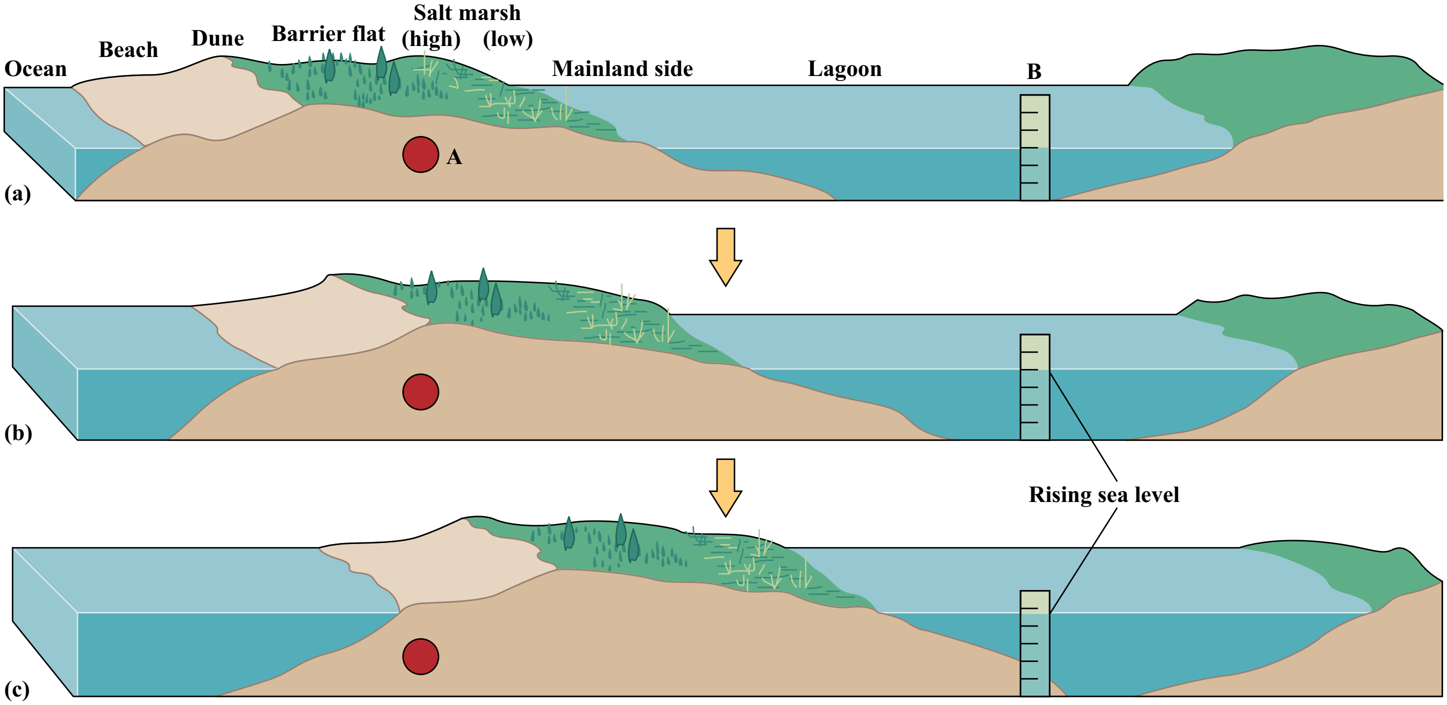


FIGURE 11-20 As sea level rises, barrier islands retreat toward the mainland as storm waves erode sand from the beach and transport it over the barrier island to accumulate on the landward side of the island. Note the sea-level rise shown at B, the inundation of the coast as sea level rises, and the landward progression of the island. Also note that the sand at point A remains in the same place during this process as the island migrates. This sand would eventually be eroded if sea level continued to rise and the barrier island continued to retreat. Vegetation stabilizes the barrier island dunes, but it is continuously eroded on the ocean side of the island and replaced by new growth on the growing landward side.

barrier islands are not fully understood. Some barrier islands may be formed from **spits** created by longshore drift, or they may be coastal sand dunes behind which rising sea level has flooded. Others may originate as a longshore bar when particularly strong storms raise the sea level and transport sand from the beach to the bar. The enlarged bar emerges when the storm has abated and sea level has dropped. Almost all possible mechanisms depend on or are aided by rising sea level.

Many or most barrier islands are thought to have been formed by erosion of the flat, sediment-filled coastal plains of passive-margin coasts as sea level rose during the past 19,000 years. As sea level rose, the soft sediments and rock of the newly flooded coastal plain were rapidly eroded, providing an abundant supply of beach sands that entered the longshore drift. As it migrated along the coast past headlands, the abundant sand accumulated downcurrent of the headlands to form spits (**Figs. 11-7, 11-19**). Spits often grow completely across the mouths of bays and inlets between two headlands to become a **baymouth bar** (**Fig. 11-19**).

As sea level rose further, the spits and bars were breached in places, allowing the sea to inundate more of the coastal plain behind the accumulated beach sands. Where sections of beach were separated from the headlands on both sides, barrier islands were formed (**Fig. 11-19**). Once formed, barrier beaches (including islands, spits, and baymouth bars) continued to be fed with large amounts of sand from the easily eroded coast and began to retreat landward in concert with the rising sea level (**Fig. 11-20**). As sea level rose, storms piled sand onto and across the barrier islands, eroding their ocean shores but building the lagoon side by the accumulation of over-washed sand (**Fig. 11-20**).

As sea level rose rapidly between about 19,000 and 4000 years ago, the barrier islands retreated with the advancing sea (**Fig. 11-20**). However, barrier beaches do not retreat continuously. The abundant sand in the long-shore drift system is accumulated on the seaward side of a barrier island until an exceptionally strong storm and elevated sea surface carry large amounts of the sand over the island. Consequently, as the barrier beaches retreated, they did not catch up to the retreating shoreline in most places. The rising sea continuously flooded more coastal plain through breaches in the barrier beach system, while the shoreline, lagoon, and barrier beach complex retreated onto the continent as sea level rose. The shorelines, lagoons, and barrier beach breaches underwent many changes in their configuration during this process. These changes were related to variations in the coastal-plain topography and in the distribution of storms along the coast.

About 4000 years ago, the rapid rise in sea level diminished, and sea level has risen only slowly since that time. The barrier beaches of the world have not yet responded completely to the virtual halt in sea-level rise, and many of them are still retreating. The retreat can be quite rapid. In some cases, barrier islands have retreated by a distance equal to their entire width within the past several decades.

Future of Barrier Islands

If sea level remains the same as it is today, barrier islands should retreat more slowly, but the retreat may be necessary for their continued existence. Abundant sand eroded from newly inundated coast is needed to sustain a barrier beach, and rising sea level is needed to prevent shallow lagoons behind the barrier island from slowly filling with sediment. If sea level remains stable, barrier islands may slowly disappear. If sea level falls significantly, barrier islands may no longer form. In contrast, more rapidly rising sea level, predicted as a consequence of enhanced greenhouse effect, will probably result in a renewed cycle of active barrier island formation and retreat.

Development on Barrier Islands

Barrier islands are particularly inviting places to build houses

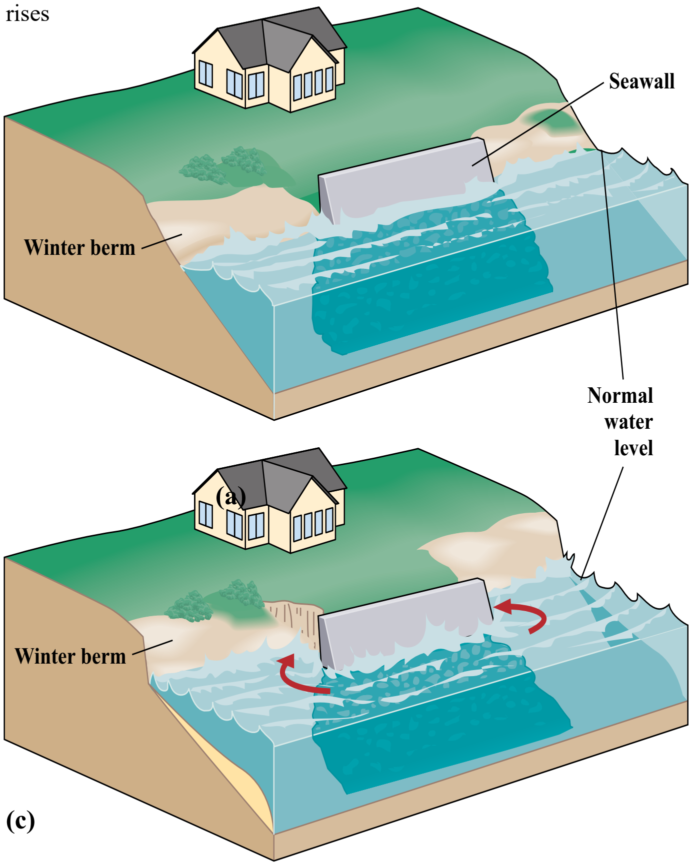


FIGURE 11-21 Seawalls are designed to protect beachfront property from erosion. (a) The Galveston seawall was constructed after the destructive hurricane of 1900. Since the wall was completed in 1962, the beach has eroded along much of its length, leaving the shoreline more exposed to attack by the highest waves of future hurricanes. (b) The barrier island has continued to retreat since the Galveston seawall was constructed. The beach just beyond the end of the wall has now retreated substantially farther shoreward than the wall's location as a result of the natural process of barrier island retreat and the consequent reduction in the amount of sand in the littoral drift system that occurred once the beach had been eroded away in front of the wall. (c) Seawalls are undermined from the sides and eventually destroyed as sea level rises

and resorts. In addition, the lagoons behind them are well suited to be harbors for small boats if the channel to the sea between islands is maintained at an adequate depth for navigation. Unfortunately, barrier beaches are dynamic features that undergo continuous change. Each time a major storm or **hurricane** hits one of the many heavily developed barrier islands, massive damage occurs and "undesirable" sand accumulates in the lagoon and often in channels. Large sums of money must be spent to rebuild and to move sand out of the lagoon and back to the depleted beach.

Although periodic destruction by storms will continue indefinitely, it may be too technologically difficult, too costly, or too environmentally undesirable to indefinitely "restore" the barrier islands as natural processes continue to cause their landward retreat. In addition, we do not know the long-term consequences of continuous beach restoration. Will the lagoon slowly fill with sediment, and will the protected shoreline marshes continue to sustain their vital **ecological** role (Chap. 13)? Clearly, if sea level rises more rapidly, the task of maintaining civilization's temporary presence on barrier islands will become increasingly difficult and expensive.

At many places on United States coasts, development has led to an endless cycle of efforts to arrest the natural landward retreat of barrier islands. Among the best known of the barrier islands are Miami Beach and Palm Beach in Florida, and Galveston and Corpus Christi in Texas. In Galveston, a **seawall** was constructed to protect houses that were rebuilt after a strong hurricane in 1900 (Fig. 11-21). However, during hurricane Ike in 2008, considerable areas of Galveston were flooded as ocean water flowed into the city mostly around the ends of the wall where the adjacent sections of the barrier island had already moved a considerable distance landward (Fig. 11-21c).

Corpus Christi has similar problems. Instead of building a seawall, the approach in Corpus Christi was to try to replenish the vanishing beach. Unfortunately, the sand used for replenishment had a larger grain size than the natural beach sand. As a result, the beach stabilized with a much steeper slope than it previously had, and thus it became more dangerous for people entering the water. In addition, beach replenishment must be repeated periodically and continued indefinitely if the beach is to be maintained. Meanwhile, the barrier island adjacent to the area where the beach is replenished continues to retreat, further increasing the exposure of Corpus Christi to ocean waves.

Both Galveston and Corpus Christi suffered flooding and considerable damage during hurricane Harvey in 2017.

BEACHES AND HUMAN STRUCTURES

The beachfront is a preferred location for constructing houses, condominiums, hotels, marinas, and other commercial establishments. Structures are built next to the beach despite the knowledge that beaches are constantly changing and subject to erosion and, hence, that the structures are vulnerable to damage by storm waves.

Most beaches migrate inland as coastal storm erosion transports sand offshore. The migration occurs more quickly in some places, particularly some barrier beaches, than in others. Nevertheless, coastal erosion continues inexorably on most coasts, carving away the base of coastal cliffs, removing sand by longshore drift, and pushing barrier islands back toward the mainland. In a few locations, beaches are built up, sometimes very rapidly, by coastal sand transport. Usually, however, beaches are built and extended seaward only where the land edge is uplifted by tectonic processes or where isostatic processes raise the land edge more quickly than erosion can occur. Accordingly, in most locations, maintenance of beachfront property requires a defense against the continual erosional loss of beach and the consequent increasing vulnerability of the property to storm waves.

When the beach in front of beachfront property loses a significant amount of sand, the traditional engineering response is to build seawalls or **groins** to restore beach sand and protect the property from wave damage. These structures interfere with the normal movement of sand in the beach system and often have unintended consequences.

Seawalls

When the beach in front of buildings or a highway has eroded or retreated so far that winter storm waves can reach and damage the structures, a seawall is often built to break up or reflect storm waves. The seawall is usually constructed parallel to the beach and behind the area of beach used by summer visitors (**Fig. 11-21**). It is made of large boulders, concrete, or steel, and either replaces or covers beach sand that normally would be mobile and eroded by the strongest winter storm waves. The wall usually works well for some years, but beach erosion continues on either end of the walled section. As the adjacent coastline retreats, the wall protrudes progressively farther seaward on the beach (**Fig. 11-21**) and is increasingly exposed to waves. Eventually the beach in front of the wall becomes very narrow, and the wall itself is undermined and eroded by waves. At this point, a continual cycle of rebuilding and destruction of the wall begins, and the beach essentially disappears.

A seawall has another unintended effect. Because it is built within the area of wave action, it prevents waves from eroding sand from what was previously the upper part of the beach. Consequently, the amount of sand carried offshore to form longshore bars is reduced. The seawall also prevents the beach from migrating landward and the waves from progressively eroding the coast to provide new sand. Thus, it reduces the amount of sand available to replace the sand lost through longshore drift. Because less sand is available, the beach becomes narrower and longshore bars are further depleted. The narrower beach and smaller longshore bars absorb less wave energy, and the wave

FIGURE 11-22 Groins designed to stop beach erosion modify the longshore sand transport and, consequently, the beach. (a) Sand accumulates on the upcurrent (longshore drift current) side of the groin and is eroded from the downcurrent side. (b) Often a line of groins is constructed along the length of a beach, which creates a saw-toothed beach shoreline like this one at Beach Haven, New Jersey. The groins will not provide effective protection as sea level rises and this barrier island recedes in the same way as Galveston island (**Fig. 11-21**. (c) You can see that the barrier island on which Beach Haven is built has already retreated in the undeveloped and unprotected area just south of the area shown in (b). Within perhaps 50 years, all the structures that you see on this barrier island will be gone or will require massive seawalls entirely around the perimeter of the island to protect them.

energy reaching and eroding the seawall increases, even though storms are no more intense.

Groins and Jetties

Beaches progressively lose sand and become narrower when structures prevent the normal erosional retreat of the coastline or when the sand supply to the longshore drift system is reduced by other means, such as the damming of rivers. When the beach erodes and narrows in front of a valuable piece of real estate, groins are often built to try to restore it. A groin is a wall built perpendicular to the beach from the backshore out to beyond the **surf zone** (Fig. 11-22a). The groin's purpose is to block the longshore drift so that sand accumulates on the upcurrent side of the groin, widening the beach at that point. The problem with groins is that they further deplete sand supply to the beach on their downcurrent side, where severe erosion may ensue. A common solution to this problem is to build another groin downcurrent from the first. Eventually a long series of groins may be built along the entire length of the beach (Fig. 11-22b). The net effect is to alter the beach so that wave erosion is enhanced on the downcurrent sides of the groins while segments of "normal"-width beach are maintained on the upcurrent sides (Fig. 11-22a). In many areas, groins are a temporary solution at best because they do not stop shoreline retreat, but merely redistribute a declining sand supply.

Other structures built on the coast also cause problems by interfering with the longshore drift system. For example, rock **jetties** are built to protect inlets between barrier beaches (Fig. 11-23). Such inlets are dynamic features that normally appear, disappear, and move up and down the coast as sand is moved

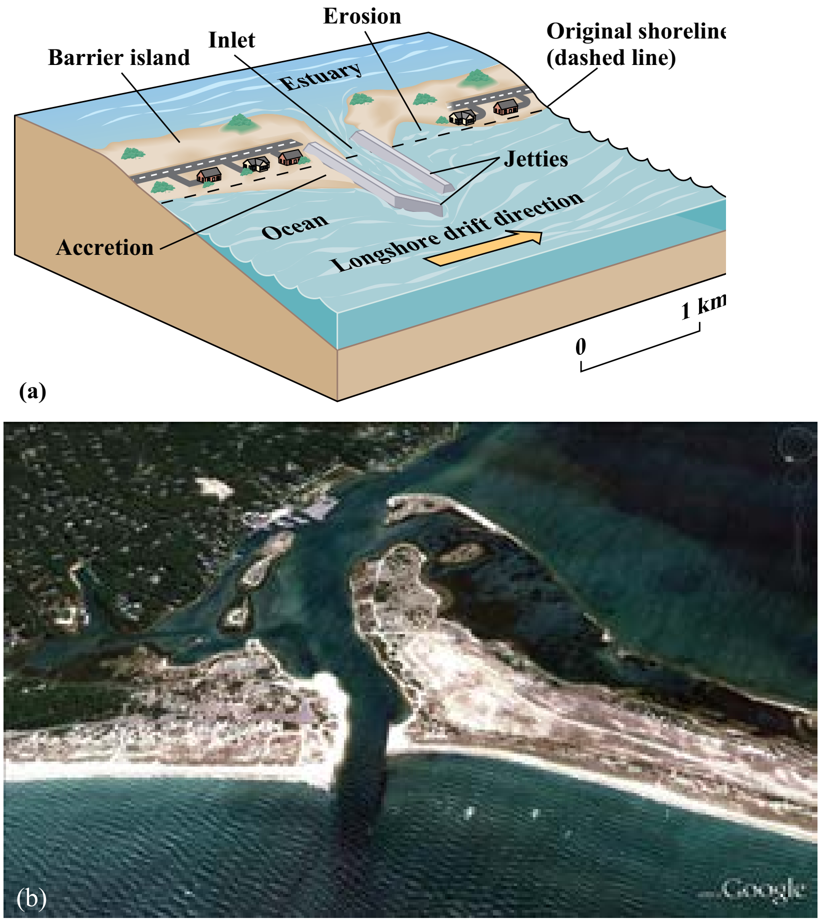


FIGURE 11-23 (Above) Jetties. (a) Rock jetties are often constructed on either side of an inlet between barrier islands to prevent silting of navigation channels and erosion of the sides of the inlet by waves from boats' wakes. These jetties obstruct the longshore sand transport, leading to the accumulation of sand and widening of the beach on the upcurrent side, and erosion and loss of the beach on the downstream side. (b) Three Mile Harbor, East Hampton, Long Island, New York. Can you tell which direction the longshore drift is?

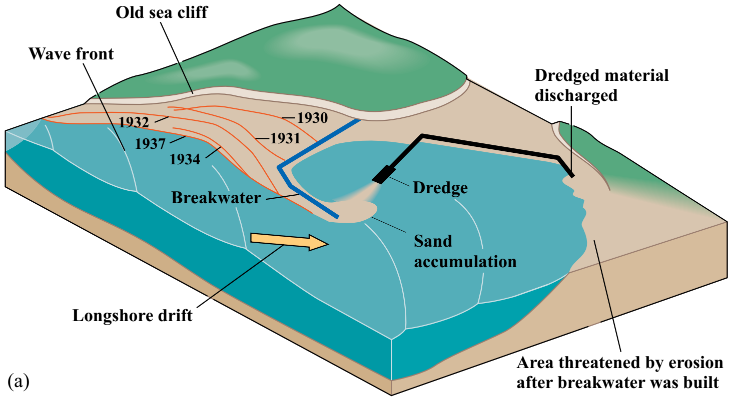


FIGURE 11-24 The jetties of the Santa Barbara harbor have interfered with the longshore drift transport system. (a) Sand has accumulated and progressively widened the beach on the north side of the main jetty (the direction from which waves most often come - the left in this photo) until the sand began to be transported south again . However, sand transported around this jetty cannot be transported across the deep harbor mouth and accumulates in a spit inside the harbor mouth. The beach on the south side of the harbor has had its supply of sand from longshore drift cut off. Periodic but continuous dredging is needed to keep the harbor from silting up. The dredged sand is deposited on the south-side beach to prevent this beach from eroding further. (b) This satellite image shows how the deeper channel in the harbor mouth provides a break in the wave pattern that interrupts the longshore drift. The object just at the exit of the inner boat harbor near the sand spit is the dredge that removes sand from the harbor and discharges it south of the harbor, back into the longshore drift system.

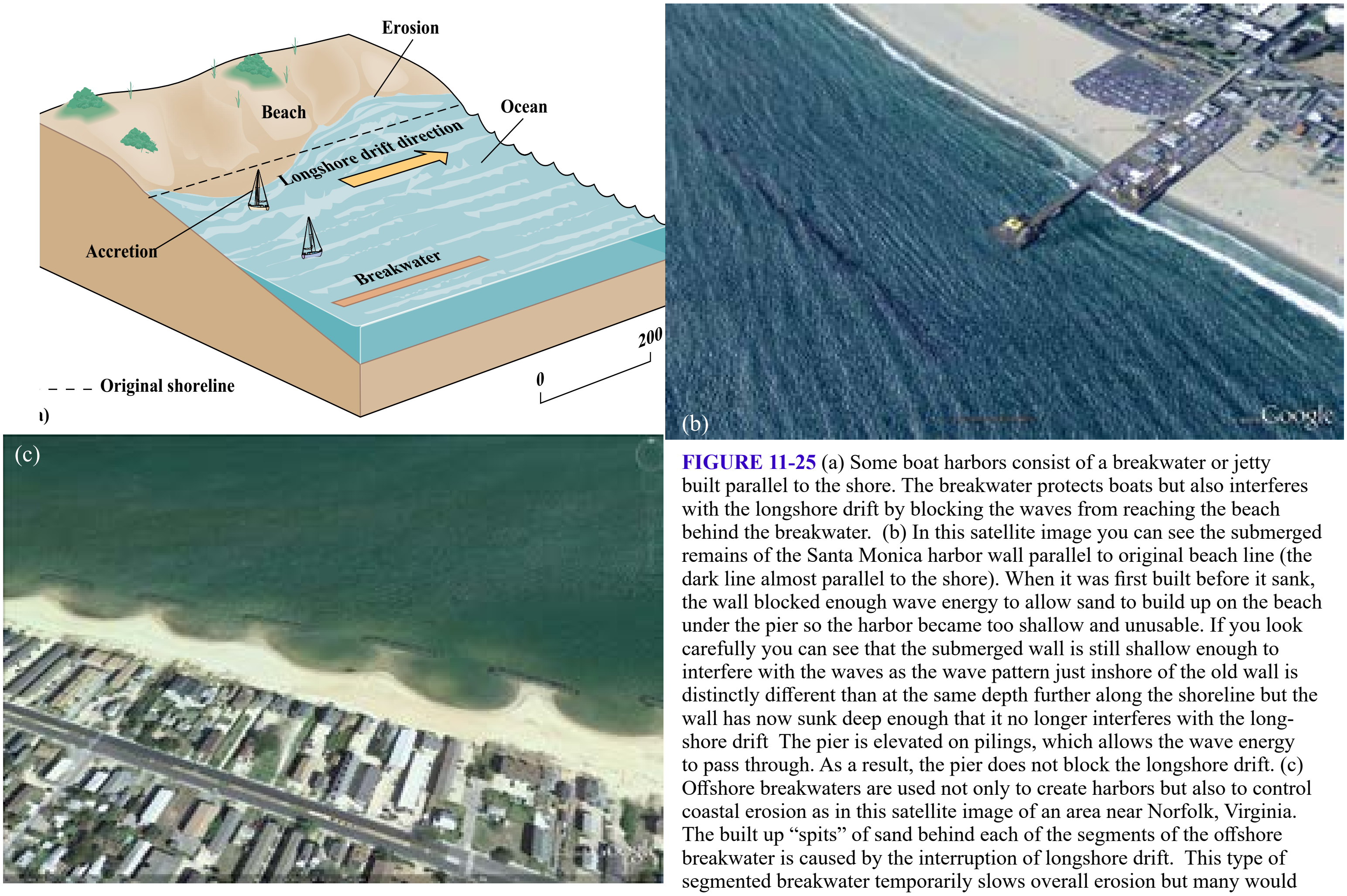


FIGURE 11-25 (a) Some boat harbors consist of a breakwater or jetty built parallel to the shore. The breakwater protects boats but also interferes with the longshore drift by blocking the waves from reaching the beach behind the breakwater. (b) In this satellite image you can see the submerged remains of the Santa Monica harbor wall parallel to original beach line (the dark line almost parallel to the shore). When it was first built before it sank, the wall blocked enough wave energy to allow sand to build up on the beach under the pier so the harbor became too shallow and unusable. If you look carefully you can see that the submerged wall is still shallow enough to interfere with the waves as the wave pattern just inshore of the old wall is distinctly different than at the same depth further along the shoreline but the wall has now sunk deep enough that it no longer interferes with the longshore drift The pier is elevated on pilings, which allows the wave energy to pass through. As a result, the pier does not block the longshore drift. (c) Offshore breakwaters are used not only to create harbors but also to control coastal erosion as in this satellite image of an area near Norfolk, Virginia. The built up "spits" of sand behind each of the segments of the offshore breakwater is caused by the interruption of longshore drift. This type of segmented breakwater temporarily slows overall erosion but many would consider that it also makes the beach unnatural and unsightly.

in the longshore drift system. Jetties stabilize an inlet by blocking waves that otherwise would erode its banks and by blocking longshore drift into the inlet that would cause **shoaling.** Beaches often become wider on the upcurrent sides of inlet jetties. In contrast, downcurrent beaches can be eroded and severely depleted of sand, and the inlet behind the island can be silted up as the island retreats inland.

Harbors

On coasts with few natural inlets, jetties or **breakwaters** commonly are built to provide a safe harbor for small boats. Two such harbor designs are shown in **Figures 11-24 and 11-25**. The dog-leg **jetty** on the upcurrent side of the Santa Barbara harbor (**Fig. 11-24**) interrupts the longshore drift so that it carries sand around the jetty but not across the deep harbor entrance, which is too deep for waves to sustain the sand movement. Sand flows around the jetty and accumulates in the harbor, making parts of the harbor too shallow for navigation. The beach that is downcurrent of the harbor is depleted of sand and threatened by severe erosion. These problems are addressed by a very expensive (millions of dollars per year), energy-intensive annual dredging project. Sand is normally dredged from the harbor, pumped through a pipeline, and discharged downcurrent, where it re-joins the longshore drift.

In the 1930s, in Santa Monica, California a harbor was created by constructing a detached breakwater offshore from the end of the Santa Monica Pier. The breakwater was a simple structure built parallel to the beach beyond the surf zone, and was designed to shelter boats. Because this breakwater did not encroach on the surf zone, it seemingly should not have interfered with the long-shore drift. Unfortunately, this was not the case, because this type of offshore breakwater prevents waves from reaching a segment of the beach behind it. Since only low-energy waves break on this segment, the longshore drift is reduced just as effectively as it would be by a groin passing through the surf zone. Soon after the Santa Barbara harbor was constructed, the beach behind the breakwater became greatly enlarged, reducing the area of safe anchorage for boats. The only solution would have been an expensive dredging program. However, the breakwater was poorly designed and quickly sank into the seabed. You can see the submerged structure in (**Fig. 11-25b**). Multiple segmented detached breakwaters are now used along many coastlines especially in Europe but their purpose is to deliberately slow down the longshore drift and maintain sand on the beach (**Fig. 11-25c**). As with other structures that attempt to slow down loss of beach sand these segmented breakwaters are, at best, a temporary solution.

CORAL REEFS AND ATOLLS

Reef-building corals are **communities** of microscopic animals that have photosynthetic **dinoflagellates**, called **zooxanthellae**, living **symbiotically** within their tissues. These reef-building corals, unlike may other corals, cannot grow successfully without the zooxanthellae or where there is not enough light for the zooxanthellae to photosynthesize. Reef-building corals also require warm water (≥18°C) and are intolerant of low **salinity** and high concentrations of **suspended sediments**. Hence, coral reefs grow only in shallow tropical and subtropical waters that are not subject to low salinity and high **turbidity** caused by stream **runoff** or abundant **plankton**.

The three basic types of coral reefs are fringing reefs, barrier reefs, and **atolls** (**Fig. 4-28**). Fringing reefs grow in shallow waters along the shore and are best developed off coasts with arid climates and where river runoff is limited. Because fringing reefs are easily damaged by excess freshwater runoff or high concentrations of suspended sediment due to storm waves, they are distributed in a patchy fashion along most coasts where they occur. Human activities such as flood-control projects, dredging, sewage discharge, and coastal modification often result in elevated concentrations of suspended sediments and enhanced runoff of low-salinity water during storms. Consequently, fringing coral reefs are damaged by these activities in many locations, but it is often difficult to distinguish damage due to human influence from natural variations.

Barrier reefs and atolls are formed only where there has been a change of sea level on the adjacent coast. If sea level rises or the coast subsides in an area that has a fringing reef, the reef grows upward. The upward growth is faster at some distance offshore where conditions are optimal. In the shallowest water close to the shoreline, wave resuspension of sediments and the effects of runoff inhibit coral growth. In deeper offshore water, reduced light levels inhibit photosynthesis by zooxanthellae and thus coral growth. Therefore, the optimal zone for coral growth is a strip of ocean some distance offshore, but not extending into deep water. The width of this zone varies with factors such as the seafloor slope and the amount of runoff. As the land subsides, the reef grows upward in this zone faster than coral can grow in either shallower or deeper water (**Fig. 4-28)**, and a barrier reef is formed (**Fig. 4-29**) Once formed, the barrier reef continues to grow upward. The rate of upward growth is usually just sufficient to match the changing sea surface level. The top of the reef remains just below the water surface, because corals are damaged if exposed to air for prolonged periods. If the maximum possible rate of upward growth is less than the rate at which the land subsides, the reef is submerged and eventually dies.

Once a barrier reef is formed, it closes or partially closes a lagoon between the reef and the coastline. Corals grow in this lagoon, but they are limited by higher turbidity due to land runoff, by salinity variations, or by lack of **nutrients** as a result of the long **residence time** of the lagoon water (**Chap. 12**, **CC8**).

Barrier reefs are especially abundant on the Earth at present because sea level has been rising eustatically for approximately the past 19,000 years. The Great Barrier Reef of Australia, which is about 150 km wide in places and more than 2000 km long, is the best-known barrier reef.

Islands formed by volcanoes on oceanic **crust** are particularly good locations for the development of barrier reefs. Once a volcanic island has moved away from the oceanic ridge or hot spot on which it was formed, it cools and sinks isostatically (**Chap. 4**, **CC2**). Hence, even in times of falling sea level, barrier reefs can be formed around such islands, as long as the island sinks faster than the sea level falls. Sinking of volcanic islands leads to the formation of the third type of coral reef, the atoll (**Figs. 4-28c, 4-27**). As the island sinks, a barrier reef develops from the fringing reef and continues to grow upward, remaining at or close to the sea surface as the island continues to sink. Eventually the island sinks entirely below the ocean surface, and its reef is left in the form of an atoll. The atoll continues to grow and maintain itself as the island sinks (or as sea level rises).

Low islands may form on an atoll, particularly on the side of the atoll from which wind and waves most often approach. Such islands are composed of debris from the reef and of calcareous algae that grow in very shallow water and can survive exposure at low tide. Islands can also be formed on an atoll by earthquakes that uplift or tilt the sinking volcano.

WETLANDS

On many shores protected from wave action, tidal wetlands develop. Tidal wetlands are flat, muddy areas covered by water during only part of the tidal cycle. Most tidal wetlands are characterized by an abundance of emergent plants: marsh grasses in salt marshes, and mangroves in mangrove swamps. Both plant types grow well in muds rich in organic matter that are inundated periodically by salt water. Grasses grow in salt marshes at all latitudes, but mangroves grow only in tropical and subtropical latitudes between about 30°N and 30°S. Where both are present, mangroves usually rapidly outgrow and eliminate marsh grasses.

Wetlands are created by the accumulation of sediments from a variety of sources. The most important are usually river-borne muds laden with organic **detritus**. Sediments accumulate in shallow protected waters, particularly at the edges of estuaries and on lagoon shores, until they extend above the low-tide line and a wetland forms.

A wetland consists of a muddy, flat terrace between the low- and high-tide lines that is dissected by shallow channels. As the tide rises, water moves through the channels and spreads over the mudflats. The current speed within the channels is faster than the water's speed as it spreads over the flats. As the speed decreases over the mudflats, suspended particles carried up the channels are deposited (**CC4**) as wetland mud. Particles of organic detritus have low **density** and can be fragmented to very small sizes. Consequently, wetlands tend to accumulate muds that are rich in organic matter, with much of the detritus contributed by the local marsh grasses or mangroves.

The abundant supply of detritus makes wetlands very attractive places for marine animals to feed and for the juvenile stages of many marine species to spend part of their life cycle before migrating to the sea. Wetlands provide not only abundant food, but also safety from predators. Large marine predators are not able to enter these shallow areas, and the grasses, mangrove roots, and abundant leaf litter offer many excellent places to hide from other predators. Wetlands have such an abundance of vegetation and juvenile marine animals that many birds use wetlands as their principal, or only, feeding areas.

Wetlands are extremely valuable ecologically, but generally they are not considered to have great scenic beauty. Therefore, because their proximity to the water makes them very attractive for development, vast areas of wetlands in the United States and elsewhere have been filled or drained. The result has been the destruction of habitat that is important for many commercially valuable fishes and **shellfish** species and a number of species of ducks and other birds. Filled wetlands are not ideal places to build or farm. Because they are low-lying, they are susceptible to flooding and to storm surges or storm waves. Structures built on former wetlands also are susceptible to subsidence as the former wetland sediments upon which they are built are compacted.

Even more importantly, structures built on filled wetlands are very vulnerable to earthquake damage. The sediments underlying structures in filled wetlands, if not properly compacted during the construction process, can be "liquefied" by the energy of earthquake waves, allowing the structures to collapse and sink. This is one of the reasons that the Loma Prieta earthquake of 1989 caused far more damage to buildings and freeways in Oakland and San Francisco, about 100 km north of the earthquake epicenter, than it did in urban areas closer to the epicenter. Most of the badly damaged or destroyed structures in Oakland and San Francisco were constructed in areas that formerly were wetlands.

DELTAS

Rivers flowing toward the sea carry eroded rock particles as suspended sediment. When they reach the flat coastal plain, river current speeds decreases because of diminishing slope and widening of the channel. Consequently, larger size fractions of suspended sediment are deposited (**CC4**). Deposited sediment slowly fills the river valley. Many rivers flow through valleys cut by glaciers or rivers when sea level was lower during the most recent **ice age,** and the lower ends of these valleys have not yet filled with sediment. Because most rivers on the east coast of the United States are in this category, they deliver little sediment to the Atlantic Ocean. Some rivers, such as the Mississippi, carry so much sediment that they have completely filled their river valleys and the bulk of their sediment is now deposited beyond the river valley to form a delta that extends out to sea. The river flows in distributary channels through the deposited sediment on the delta, and in some places, such as the Mississippi delta, the channels pass through long extensions or lobes of these deposits (**Fig. 11-5**).

Deltas resemble wetlands in function. During normal river flow, relatively small quantities of suspended sediment are transported down the narrow river channels and deposited in the channel or carried out to sea. When the river floods, much larger quantities of sediment are brought downstream into the delta, but the river overflows its banks and inundates the flat land of the delta. The current speed of river water decreases as it leaves the channels and spreads across the delta, allowing suspended sediment to be deposited. Sediment distribution across the delta is aided by the river's occasional abandonment of channels and creation of new ones (**Fig. 11-5**). In this way, surface soils of the delta are periodically enriched by additions of organic matter and nutrients from the river.

In some deltas, the deposition rate has been high enough that large quantities of organic-rich muds have been continuously buried by newly deposited sediments over long periods of geological time. These buried sediments are compacted by the overlying layers, water is squeezed out, and in many such areas, oil and gas deposits have been formed as the organic matter has decomposed. Many oil and gas deposits are located in deltas or offshore in areas where deltas existed when sea level was lower. Major deltas of the world include the Mississippi delta, the San Francisco Bay delta, the Copper River delta in Alaska, the Mackenzie delta in northwest Canada, the Nile delta in Egypt, the Niger delta in Nigeria, and the Ganges–Brahmaputra delta in Bangladesh and India.

Muddy delta soils are slowly compacted as water is squeezed out of them by the weight of overlying sediment. This process can be accelerated by the weight of structures built on the delta. In addition, the organic matter in the delta soils decomposes if it is not buried by additional river-borne sediments, and the soils themselves are further eroded by winds and rainfall. Therefore, periodic influxes of new sediment are needed to maintain the delta land surface slightly above sea level.

Because they are particularly rich in nutrients and organic matter, delta soils are among the best for agriculture. Consequently, many deltas, such as the Mississippi delta, are populated and intensively farmed. Unfortunately, deltas are also very easily flooded. Almost the entire population of Bangladesh lives on a delta that is regularly inundated by swollen rivers and hurricane storm surges (**Chap. 9**), often with great loss of life.

To control the frequent flooding of two major deltas in the United States—the Mississippi delta and the San Francisco Bay delta—extensive engineering projects have been carried out in which banks called **levees** have been built along each side of the river channels. Levees have worked extremely well by some measures because they have dramatically reduced flooding, but they also have unintended consequences. Without the periodic influx of nutrient-rich suspended sediment to the delta during floods, the fertility of the soils steadily declines. In addition, without the periodic inputs of new soil, the land slowly sinks as soil compacts and erodes. Sinking of the land surface is actually accelerated by agriculture through increased soil erosion and decomposition of soil organic matter. Worse still, withdrawal of freshwater from aquifers beneath the delta further accelerates sinking, particularly in the Mississippi delta.

As the land sinks in the Mississippi and San Francisco Bay deltas, more and higher levees are needed to prevent flooding. In the San Francisco Bay delta, most of the land is now meters below the normal river water level. Any breach of the levee allows the land to be covered completely with water, even when the river is not swollen by flood rainwater. For example, a 100-m-wide breach occurred in a levee in the San Francisco Bay delta in the summer of 2004. The breach flooded nearly 50 km^2 of farmland, destroying crops, homes, and other structures. It took about 200,000 tonnes of rock to seal the levee breach. The total cost of the crops and structures destroyed, repairing the levee, and pumping water out of the flooded land was nearly $100 million. Significant as this event was, it was just a foretaste of the devastation, chaos, and loss of life and property that was caused by the breaks in the protective levees of New Orleans that flooded most of that city to a depth of up to 10 m or more in 2005 following the passage of hurricane Katrina.

Higher and stronger levees could be built, but they would be very expensive and difficult to construct because they would need to be capable of restraining increasing **hydrostatic pressure** as the delta floor sinks and sea level rises. In addition, levees constrain the river to flow very swiftly through a narrow channel, so erosion of existing levees is a major problem and would remain so even if levees were enhanced.

What is the future of the Mississippi and San Francisco Bay deltas, particularly if global climate change causes sea level to rise more quickly? If we continue on our present course, these delta lands will continue to sink, and levees will continue to be built higher until holding back the water becomes impossible. Meanwhile, soils will become impoverished and the land's agricultural value will decline. One alternative is to tear down the levees. Within a few years or decades, the deltas would return to their normal functioning, and valuable agricultural lands would again be available for the future. If we are to retain the highly productive deltas, the price we must pay is periodic flooding.

In Louisiana, where the levees on the Mississippi delta have been a major contributor to the loss of an average of about 65 km^2 of coastal land per year since 1930, and in the San Francisco Bay Delta programs have begun to establish breaches in the levees that will replenish delta sediments in key areas, converting these areas back to wetlands. So far, on the Mississippi Deltas, the program has focused mainly on areas that had become shallow coastal lagoons as a result of the levee diversions of sediments. Strong opposition to the program from fishers who used the lagoons to collect oysters had to be overcome. Even greater opposition is, and will continue to be, encountered when the proposed replenishments involve land that has been drained for agriculture. It remains to be seen whether these replenishment programs will ultimately succeed and can be applied to other Deltas.

CHAPTER SUMMARY

Processes That Form and Modify the Coastline.

Coasts can be erosional or depositional. Primary coasts are formed by volcanoes, earthquake movements, landslides, deposition of river-borne sediment, and sea-level change. Sea level has risen about 130 m in the past 19,000 years and continues to rise. Secondary coasts are formed by erosion or deposition by waves, tidal and ocean currents, and the formation of coral reefs.

Beaches.

The littoral zone extends between the seaward boundary of land vegetation and the depth where wave action does not disturb the sediments (about 10 to 20 m). Beaches are part of the littoral zone and consist of a back-shore, foreshore, and offshore. The backshore is normally dry at high tide and may be characterized by berms created by storm waves. The foreshore is the gently sloping area between the high- and low-tide lines, where scarps may form. The offshore extends seaward of the low-tide line and may have a longshore bar near its seaward boundary.

Beaches are a mixture of grains of varied composition supplied by erosion or by longshore drift. Longshore drift, caused by the incomplete **refraction** of waves, transports sand downcoast of the direction from which the waves approach. Sand is moved along the coast until it is transported down a submarine canyon. Some beaches may be in danger of losing sand because the supply of river-borne sand to the longshore drift system has been reduced by dams and other factors.

Particles that make up a beach are sorted by waves. Small particles are removed to deep water. Large particles are not moved by longshore drift and are present only if they are formed locally by the erosion of cliffs next to the beach. Grain size is larger on beaches with greater wave action. Quiet beaches are composed of fine-grained sand, whereas those with greater wave action are composed of coarse-grained sand or gravel.

Large winter waves move sand from the beach offshore to build a longshore bar. In summer, gentler waves return sand to the beach. In winter, a beach is narrower with a flat foreshore and steep backshore. In summer, the beach is broader, the foreshore is steeper and a summer berm or berms are formed. Beach slope increases as grain size of the beach materials increases.

Barrier Islands and Lagoons.

Barrier islands protect the coast from wave erosion and enclose lagoons that are nursery areas for many marine species. They are formed and maintained by sand that is moved by longshore drift. Barrier island–lagoon systems are retreating landward as sea level rises. Development on barrier islands presents problems because of this landward migration. Dredging of the lagoons and beach replenishment are necessary to reverse migration that would destroy developed structures on the islands, but these measures cannot be successful indefinitely. Developments on barrier islands repeatedly sustain expensive damage when major storms occur.

Beaches and Human Structures.

As beaches migrate inland or lose sand because river sources are reduced, seawalls and groins are built to retain the sand or protect coastal structures. Seawalls temporarily protect coastal structures from waves, but eventually they are undermined and destroyed as the shoreline recedes. Seawalls also reduce erosion that would otherwise supply sand to the longshore drift system, and consequently, they reduce beaches and longshore bars that would absorb wave energy. Groins are built across the littoral zone to retain sand on beaches by blocking longshore drift. Sand builds up on the upcurrent side of the groin and is lost from the downcurrent side. Groins are often only temporarily effective and can cause a loss of sand on down-current beaches that leads to the building of more groins. Jetties or breakwaters protect harbors from wave action but interfere with longshore drift and often cause sediment to accumulate in the harbor, making continuous dredging necessary.

Coral Reefs and Atolls.

Reef-building corals grow only in warm water shallow enough that their zooxanthellae can photosynthesize. They grow best in waters with lower turbidity and little salinity variation. Fringing coral reefs grow in shallow water off shores where erosion and freshwater inputs are low. Barrier reefs and atolls form where coral growth is faster some distance offshore than immediately along the shore, and where sea level rises or the coast subsides. Most atolls are formed from barrier reefs as volcanoes sink isostatically below the sea surface.

Wetlands.

Tidal wetlands are flat, muddy areas covered by water part of the time. They retain detritus from river flow and vegetation that grows in them. The detritus provides food and the grasses and shallow water provide shelter for juveniles of many marine species. Large areas of coastal wetlands have been filled for development.

Deltas.

Deltas are formed after sediments fill river valleys and then accumulate at the mouth of the river. They are flat areas maintained at an elevation slightly above sea level by periodic river floods that bring sediment, detritus, and nutrient-containing particles to be deposited on the flooded delta. They are good agricultural land because of these periodic inputs, but they are often flooded. Although levees have been built to protect many deltas from flooding, these structures cut off the supply of new sediment, so the land slowly subsides, is eroded away, and loses its nutrients and detritus.

KEY TERMS

You should be able to recognize and understand the meaning of all terms that are in boldface type in the text. All of those terms are defined in the Glossary (p. 000). The following are some less familiar key scientific terms that are used in this chapter and that are essential to know and be able to use in classroom discussions or on exams.

atoll
backshore
backwash
barrier island
barrier reef
baymouth bar
beach
berm
breakwater
coast
coastal plain
coastal zone
coastline
coral reef
delta
depositional
erosional
estuary
eustatically
fjord
foreshore
fringing reef
groin
high-tide line
hydrostatic pressure
isostatic leveling
jetty
lagoon
levee
littoral drift
littoral zone
longshore bar
longshore current
longshore drift
low-tide line
low-tide terrace
mangrove
orbital velocity
reef
resuspend
rip current
runoff
salt marsh
sand dune
scarp
sea grass
seawall
shore
shoreline
sorted
spit
storm surge
submarine canyon
surf zone
swash
symbiotically
tidal range
turbidity
weathered
wetland

STUDY QUESTION

1. Describe the processes that modify a coastline once it has been formed. How and why are the coastlines of passive and active margins different?
2. Describe the features of a beach at the end of a summer in which no large storm waves arrived at the beach. How would these features change if a storm with very large waves hit the shoreline?
3. Why are the particles of sand on most beaches limited to a narrow range of sizes? Why can the size ranges be different on two beaches located near each other?
4. Where does beach sand come from, and how is sand moved along a coastline?
5. It has been proposed that the energy of waves can be harnessed by various devices placed seaward of the surf line. If many such devices extended along a coastline and they collected a substantial fraction of the incoming wave energy, how would the beaches be changed?
6. Why is replacing sand lost from a barrier island beach, or building a seawall to protect beachfront property, only a temporary solution for beach erosion?
7. In many indented bays there is a wide, flat, sandy beach at the bay's center. but the beach disappears near each headland. Another sandy beach is usually found in the next bay. Describe the processes responsible for this distribution of beach sand.
8. Why don't fringing coral reefs grow on all tropical coastlines? What is the relationship between rising sea level and the number and distribution of atolls and barrier reefs in the oceans?
9. Describe the differences between fringing coral reefs, barrier reefs, and atolls. The island of Hawaii has mostly fringing reefs. Why?
10. What are the important physical, biological, and geological features of a wetland? Many wetlands have had roads built across them, either on gravel or dirt roadbeds or on elevated concrete pilings. Which type of road is environmentally preferred and why? What could be done to lessen the impact of the lesser-preferred option, short of rebuilding it?

CRITICAL THINKING QUESTIONS

1. In the Hawaiian Islands the youngest island, Hawaii, is the biggest, has sandy beaches along the smallest fraction of its coastline, and has more black sand beaches than the other islands. Oahu, which is older than Hawaii, is smaller, has a greater fraction of its coastline occupied by beaches, and does not have black sand beaches. Kauai, which is older than both Oahu and Hawaii, is smaller than either of these other islands, has the largest fraction of its coastline occupied by beaches, and also does not have black sand beaches. Explain why this progression of island characteristics with age occurs. (These processes are described individually in several different chapters of this text.)
2. Sea level may soon begin to rise faster than has ever occurred in the history of the Earth. Hypothesize the possible effects of such a rapid sea-level rise on the number and health of coral reefs in the world's oceans and on the geographic extent and distribution of wetlands.
3. Describe and explain what happens to deltas when humans build levees to prevent frequent flooding. Many lives and huge expenditures needed to fix property damage have been saved by the construction of levees on the Mississippi and San Francisco Bay deltas. Deltas in other parts of the world, such as the delta on which most of the population of Bangladesh lives and farms, are still regularly flooded by hurricane storm surges or intense monsoon rains, often with great loss of life and damage to property.
    - (a) Discuss what you think should be done to manage the Mississippi River, San Francisco Bay, and Bangladesh deltas in the future.
    - (b) What information should be considered in making such decisions?
    - (c) How do you think these decisions should be made, and by whom?
4. Describe barrier islands and how they form and move. Explain why rising sea level is important for barrier island formation, and discuss what would happen to barrier islands if sea level were to fall. 11-5 Privately owned houses on barrier islands may be severely damaged by hurricanes.
    - (a) Should these be rebuilt?
    - (b) Many of the owners of such homes have no flood insurance. Should federal disaster funds be used to help them rebuild their homes?
    - (c) If it is decided that these homes should not be rebuilt, should the owners be compensated? If so, how and by whom?
5. Imagine that you are a member of the U.S. Congress repre-

senting a district that includes a barrier island community, such as Miami Beach or Galveston, that has just been hit by a hurricane causing such extensive property damage that many homes and hotels near the beach must be torn down. The existing seawall is clearly too low to fully protect the community from future hurricanes. You are aware that emissions of greenhouse gases during the past century will almost certainly result in climate warming, more rapidly rising sea level, and increased intensity and frequency of hurricanes. You are also aware that any reduction in the current rate of greenhouse gas emissions will be very expensive and probably detrimental to the economy. Furthermore, it will only slow, not stop, the warming trend, and it will have no effect unless other nations also reduce their use of fossil fuels, including those underdeveloped nations that need to increase such use if they are to improve their living standard. The national budget deficit is getting worse, and money for social programs is being reduced.

   (a) On the basis of what you have learned about barrier islands, the effects of sea-level rise, and the current state of knowledge of the enhanced greenhouse effect, what would you do?
   (b) Discuss your reasons for choosing the action or course of actions that you have chosen.
   (c) Would you feel differently if you owned a home on the barrier island in question? If so, how and why?
   (d) Would you feel differently if you represented a congressional district in Colorado? If so, how and why?

6. Explain what happens to a beach if a solid jetty is built out through the surf zone. Describe how the situation might be different if the jetty were built on widely spaced pilings.
7. What would happen to the beach if a solid jetty were built at an angle of 45° instead of at right angles to the beachfront? Explain your answer.
8. Why are there few deltas in the United States? In the next few million years, where would you expect to see new deltas form in the United States? Explain why.

CRITICAL CONCEPTS REMINDERS

CC2 Isostasy, Eustasy, and Sea Level: Earth's crust floats on the plastic asthenosphere. Sections of crust rise and fall isostatically as temperature changes alter their density or as their mass loading changes. This, in turn, causes isostatic changes of sea level. Eustatic changes of sea level occur globally when the volume of water in the oceans changes or when the volume of the ocean basins themselves change. Sea level changes create new coasts. Oceanic crust cools progressively after it is formed and sinks because its density rises. Thus, the hot spot volcanic islands slowly sink after they move away from the hot spot.

CC4 Particle Size, Sinking, Deposition, and Resuspension: Suspended particles in the ocean sink at rates primarily determined by particle size: large particles sink faster than small particles. Once deposited, particles can be resuspended if current speeds are high enough. Generally large particles are more difficult to resuspend, although some very fine particles may be cohesive and therefore, also difficult to resuspend. Sinking and resuspension rates are primary factors in determining the grain size characteristics of beach sands and sediments at any given location.

CC8 Residence Time: The residence time of seawater in a given segment of the oceans is the average length of time the water spends in that segment. In restricted arms of the sea, such as lagoons behind barrier islands and fringing reefs, residence time can be long, in which case the nutrients may be depleted, limiting the growth of corals and other marine species.

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