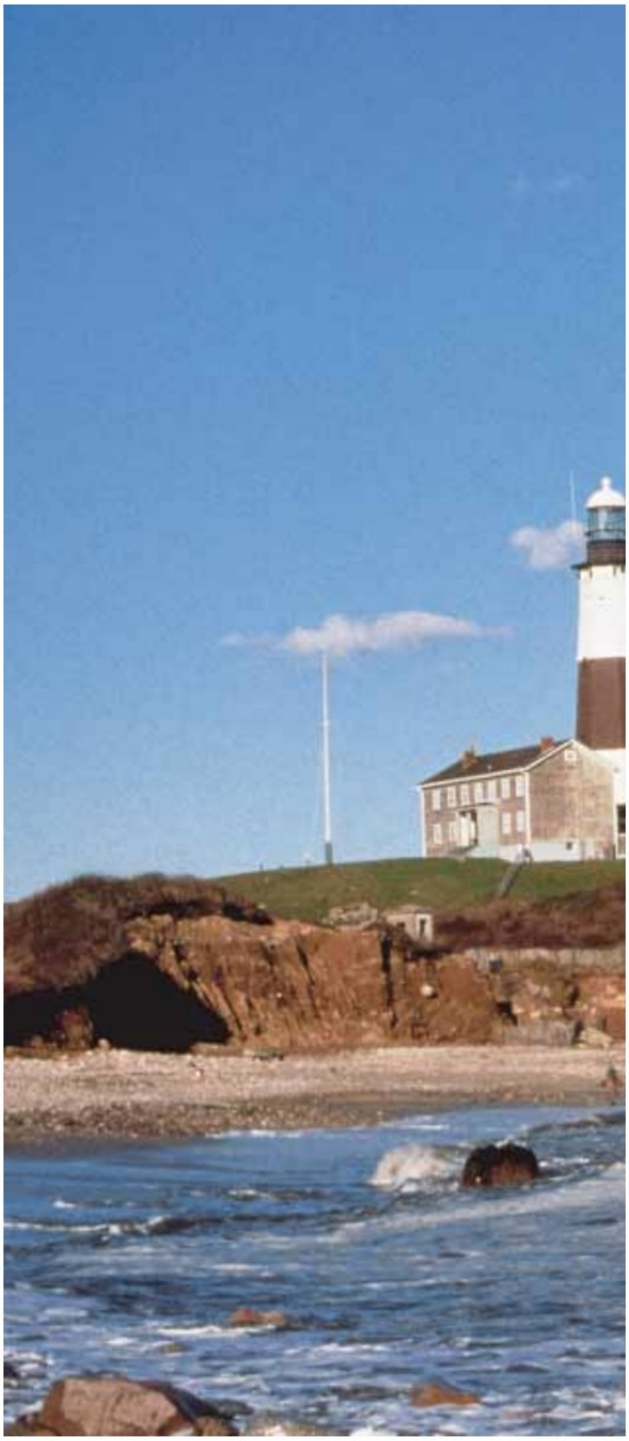
CHAPTER

18

# Coastlines

The seashore is an attractive place to live or visit. Because the ocean moderates temperature, coastal regions are cooler in summer and warmer in winter than continental interiors. People enjoy the salt air and find the rhythmic pounding of surf soothing and relaxing. Vacationers and residents sail, swim, surf, and fish along the shore. In addition, the sea provides both food and transportation. For all of these reasons, coastlines have become heavily urbanized and industrialized. In the United States, 75 percent of the population, 40 percent of the manufacturing plants, and 65 percent of the electrical power generators are located within 80 kilometers of the oceans or the Great Lakes.

Coastlines are also one of the most geologically active environments on Earth. Rivers deposit great amounts of sediment on coastal deltas. Waves and currents erode the shore and transport sediment. Converging tectonic plates buckle many coastal regions, creating mountain ranges, earthquakes, and volcanic eruptions. Over geologic time, sea level rises and falls, flooding some beaches and raising others high above sea level.



Coastlines are among the most changeable landforms. Montauk Point, Long Island, is composed of glacial till deposited during the last Ice Age. Waves and currents are eroding the Point and carrying the sediment westward.

## 18.1 WAVES, TIDES, AND CURRENTS

### OCEAN WAVES

Most waves develop when wind blows across the water. Waves vary from gentle ripples on a pond to destructive giants that can topple beach houses during a hurricane. In deep water, the size of a wave depends on (1) the wind speed, (2) the length of time that the wind has blown, and (3) the distance that the wind has traveled (sailors call this last factor **fetch**). A 25-kilometer-per-hour wind blowing for 2 to 3 hours across a 15-kilometer-wide bay will generate waves about 0.5 meter high. But if a Pacific storm blows at 90 kilometers per hour for several days over a fetch of 3500 kilometers, it can generate 30-meter-high waves, as tall as a ship's mast.

The highest part of a wave is called the **crest**; the lowest is the **trough** (Fig. 18–1). The **wavelength** is the distance between successive crests. The **wave height** is the vertical distance from the crest to the trough.

If you tie one end of a rope to a tree and shake the other end, a wave travels from your hand to the tree, but any point on the rope just moves up and down (Fig. 18–2). In a similar manner, a single water molecule in a water wave does not travel in the same direction as the wave. The water molecule moves in circles, as shown in Figure 18–3. Water at the surface completes relatively small circles with little forward motion. That is why if you are sitting in a boat on the ocean, you bob up and down and sway back and forth as the waves pass beneath you, but you do not travel along with the waves. In addition, the circles of water movement become smaller with depth. At a depth equal to about one half the wavelength, the movement becomes negligible. Thus, if you dive deep enough, you escape wave motion.

In deep water, therefore, the bottom of a wave does not contact the sea floor. But when a wave enters shallow water, the deepest circles interact with the bottom

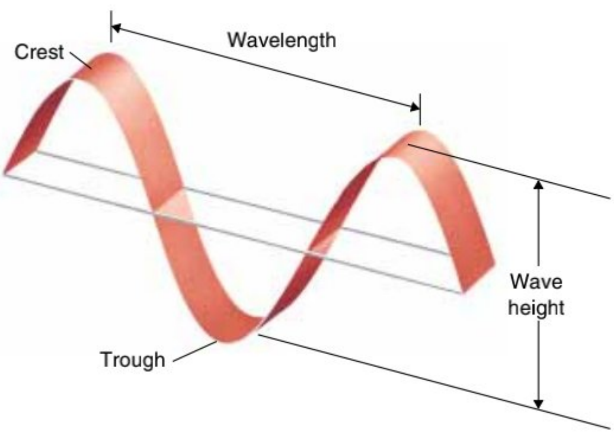



**Figure 18–1** Terminology used to describe waves.

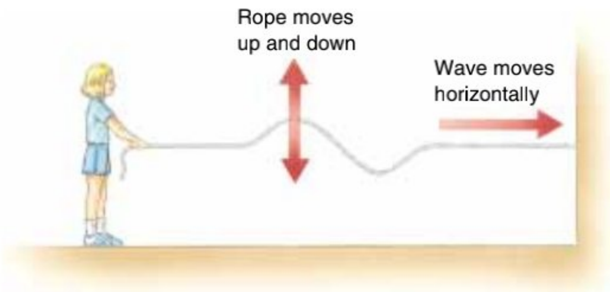



**Figure 18–2** When a wave moves along a rope, any point moves up and down, but the wave travels horizontally.

and are compressed into ellipses. This deformation slows the lower part of the wave, so that the upper part moves more rapidly than the lower. As a result, the front of the wave steepens until it collapses forward, or **breaks** (Fig. 18–4). Chaotic, turbulent waves breaking along a shore are called **surf**.

#### *Wave Refraction*

Most waves approach the shore obliquely rather than directly. When this happens, one end of the wave encounters shallow water and slows down, while the rest of the wave is still in deeper water and continues to advance at a constant speed. As a result, the wave bends. This effect is called **refraction**. Consider the analogy of a sled gliding down a snowy hill onto a cleared road. If the sled hits the road at an angle, one runner will reach it before the other. The runner that hits the pavement first slows down, while the other, which is still on the snow, continues to travel rapidly (Fig. 18–5). As a result, the sled turns abruptly.

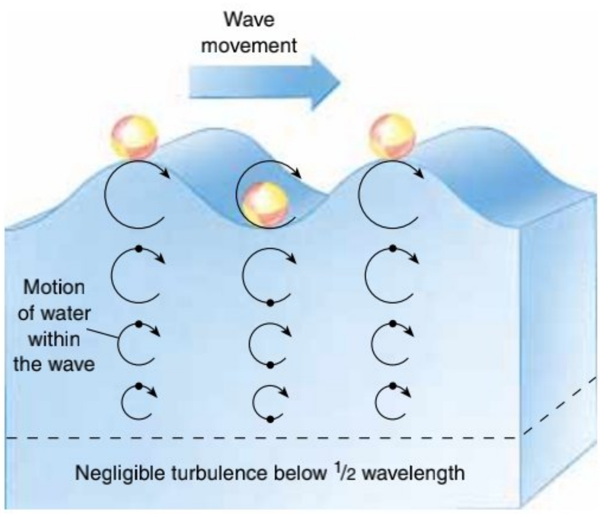
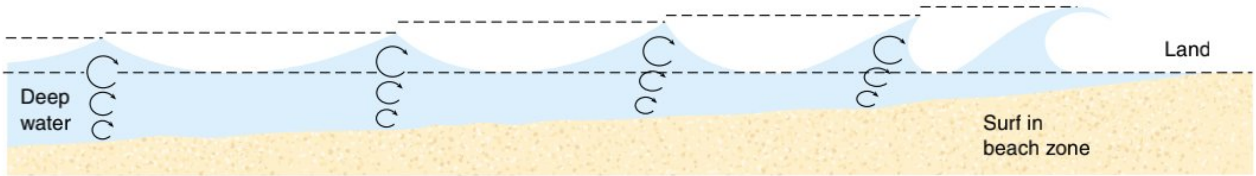



**Figure 18–3** Movement of a wave and the movement of water within the wave.

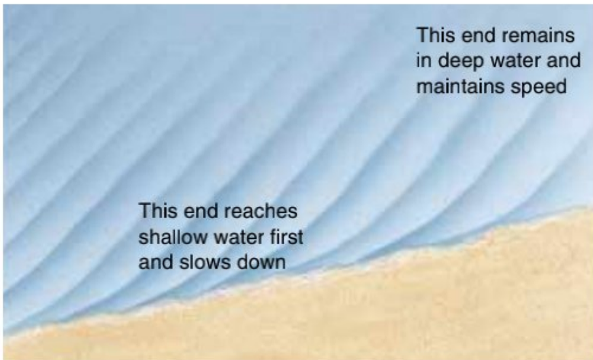



(a)

(b)

**Figure 18–4** (a) When a wave approaches the shore, the circular motion flattens out and becomes elliptical. The wavelength shortens, and the wave steepens until it finally breaks, creating surf. The dashed line shows the changes in wavelength and wave height as the wave approaches shore. (b) Surf breaks along the beach in Hawaii. (Corel Photos)


(a)




(b)

(c)

**Figure 18–5** (a) A sled turns upon striking a paved roadway at an angle because one runner hits the roadway and slows down before the other does. (b) When a water wave strikes the shore at an angle, one end slows down, causing the wave to refract, or bend. (c) Wave refraction on a lakeshore.

## TIDES

Even the most casual observer will notice that on any beach the level of the ocean rises and falls on a cyclical basis. If the water level is low at noon, it will reach its maximum height about 6 hours later, at 6 o'clock, and be low again near midnight. These vertical displacements are called **tides**. Most coastlines experience two high tides and two low tides approximately every 24 hours.

Tides are caused by the gravitational pull of the Moon and Sun. Although the Moon is much smaller than the Sun, it is so much closer to the Earth that its influence predominates. At any time, one region of the Earth (marked A in Fig. 18–6) lies directly under the Moon. Because gravitational force is greater for objects that are closer together, the part of the ocean nearest to the Moon is attracted with the strongest force. The water rises, resulting in a high tide in that region. (Although land also experiences a gravitational attraction to the Moon, it is too rigid to rise perceptibly.)

But now our simple explanation runs into trouble. As the Earth spins on its axis, a given point on the Earth passes directly under the Moon approximately once every 24 hours, but the period between successive high tides is only 12 hours. Why are there ordinarily two high tides in a day? The tide is high not only when a point on Earth is directly under the Moon, but also when it is 180° away. To understand this, we must consider the Earth–Moon orbital system. Most people visualize the Moon orbiting around the Earth, but it is more accurate to say that the Earth and the Moon orbit around a common center of gravity. The two celestial partners are locked together like dancers spinning around in each other's arms. Just as the back of a dancer's dress flies outward as she twirls, the oceans on the opposite side of the Earth from the Moon bulge outward. This bulge is the high tide 180° away from the Moon (point B in Fig. 18–6). Thus, the tides rise and fall twice daily.

High and low tides do not occur at the same time each day, but are delayed by approximately 50 minutes every 24 hours. The Earth makes one complete rotation on its axis in 24 hours, but at the same time, the Moon is orbiting the Earth in the same direction. After a point on the Earth makes one complete rotation in 24 hours, that point must spin for an additional 50 minutes to catch up with the orbiting Moon. This is why the Moon rises approximately 50 minutes later each night and the tides are approximately 50 minutes later each day.

Although the Sun's gravitational pull on the Earth's oceans is smaller than the Moon's, it does affect ocean tides. When the Sun and Moon are directly in line, their gravitational fields are added together, creating a strong tidal bulge. During these times, the variation between high and low tides is large, producing **spring tides** (Fig. 18–7a). When the Sun and Moon are 90° out of alignment, each partially offsets the effect of the other and the differences between the levels of high and low tide are smaller. These relatively small tides are called **neap tides** (Fig. 18–7b).

Tidal variations differ from place to place. For example, in the Bay of Fundy, the tidal variation is as much as 15 meters during a spring tide, while in Santa Barbara, California, it is less than 2 meters. Mariners consult tide tables that give the time and height of the tides in any area on any day.

## OCEAN CURRENTS

A wave is a periodic oscillation of water. In contrast, a current is a continuous flow of water in a particular direction. Currents are found everywhere in the ocean, from its surface to its greatest depths.

### *Surface Currents*

Prevailing winds push the sea surface to generate broad, slow, surface currents that are deflected into circular paths by the Earth's rotation. One familiar ocean current is the Gulf Stream, which flows from the Caribbean Sea northward along the east coast of North America and

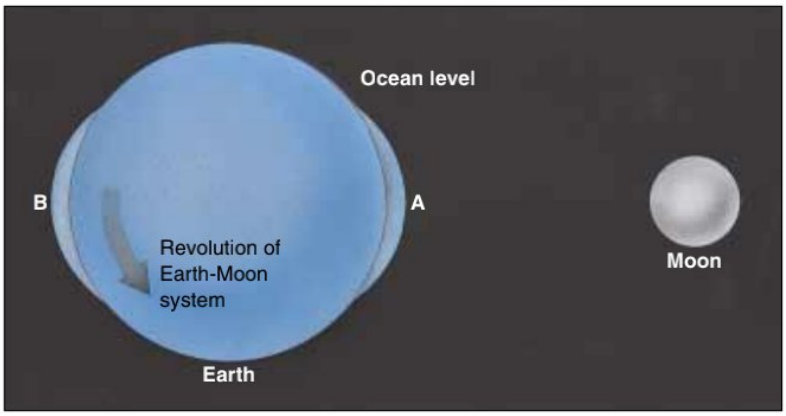



**Figure 18–6** Schematic view of tide formation. (Magnitudes and sizes are exaggerated for emphasis.)

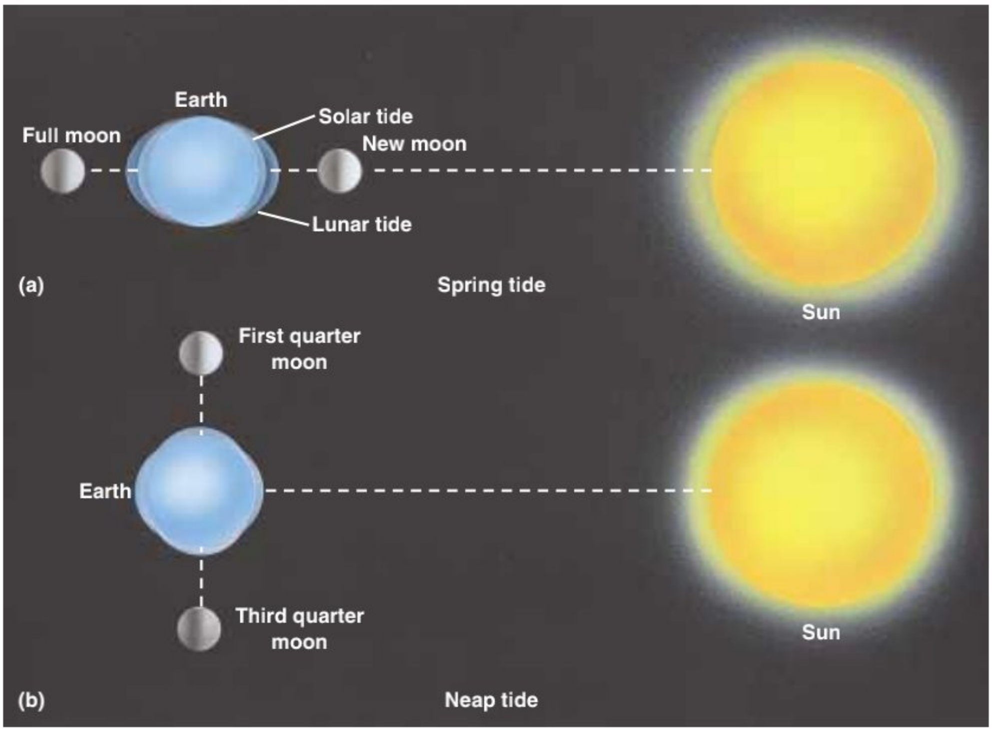



**Figure 18–7** Formation of spring and neap tides.

then across the Atlantic Ocean to Europe. Ocean currents affect climates by carrying warm water from the equator toward higher latitudes or cold water from the Arctic and Antarctic toward lower latitudes.

### *Currents Generated by Tides*

When tides rise and fall along an open coastline, the water moves in and out as a broad sheet. If the tidal flow is constricted by a narrow bay, a fjord, islands, or other obstructions, the moving water is funneled into **tidal currents**. Tidal currents can be intense where large differences exist between high and low tide and where narrow constrictions occur in the shoreline. In parts of the west coast of British Columbia, a diesel-powered fishing boat cannot make headway against tidal currents flowing between closely spaced islands. Fishermen must wait until the tide and tidal currents reverse direction before passing through the constrictions.

### *Currents Generated by Near-Shore Waves*

After a wave breaks and washes onto the beach, the water flows back toward the sea. This outward flow creates a current called a **rip current**, or **undertow**, that can be strong enough to carry swimmers out to sea.

If waves regularly strike shore at an angle, they create a **longshore current** that flows parallel to the beach (Fig. 18–8). A longshore current flows in the surf zone and a little farther out to sea and may travel for tens or even hundreds of kilometers. When waves strike shore at an angle, they wash sand onto the beach in the direction that they are moving. However, the water then flows straight back down the beach slope, taking some of the sand with it. The zig-zag motion carries sand along the coast in a process called **beach drift**.

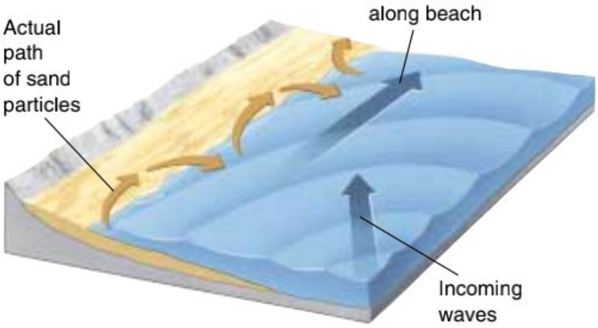



**Figure 18–8** Formation of a longshore current.

(a)

(b)

**Figure 18–9** (a) Sandy beaches are common near Santa Barbara, California. (b) Big Sur, to the north, is dominated by rocky beaches.

## 18.2 THE WATER'S EDGE

### BEACHES

When most people think about going to the beach, they think of gently sloping expanses of sand. However, a **beach** is any strip of shoreline that is washed by waves and tides. Most beaches are covered with sediment. Although many beaches are sandy, others are swampy, rocky, or bounded by cliffs (Fig. 18–9).

A beach is divided into two zones, the **foreshore** and the **backshore**. The foreshore, called the **intertidal zone** by biologists, lies between the high and low tide lines and is alternately exposed to the air at low tide and covered by water at high tide. The backshore is usually dry but is washed by waves during storms. Many terrestrial plants cannot survive even occasional inundation by salt water, so specialized, salt-resistant plants live in the backshore. The backshore can be wide or narrow depending on its topography and the frequency and intensity of storms. In a region where the land rises steeply, the backshore may be a narrow strip. In contrast, if the coast consists of low-lying plains and if coastal storms occur regularly, the backshore may extend several kilometers inland.

**Figure 18–10** Reefs grow in the clear, shallow water near Vanuatu and many other South Pacific islands.

### REEFS

A **reef** is a wave-resistant ridge or mound built by corals, oysters, algae, or other marine organisms. Because corals need sunlight and warm, clear water to thrive, coral reefs develop in shallow tropical seas where little suspended clay or silt muddies the water (Fig. 18–10). As the corals die, their offspring grow on their remains. Oyster reefs form in temperate estuaries and can grow in more turbid water.

The South Pacific and portions of the Indian Ocean are dotted with numerous islands called atolls. An **atoll** is a circular coral reef that forms a ring of islands around a lagoon. Atolls vary from 1 to 130 kilometers in diameter and are surrounded by deep water of the open sea. If corals live only in shallow water, how did atolls form

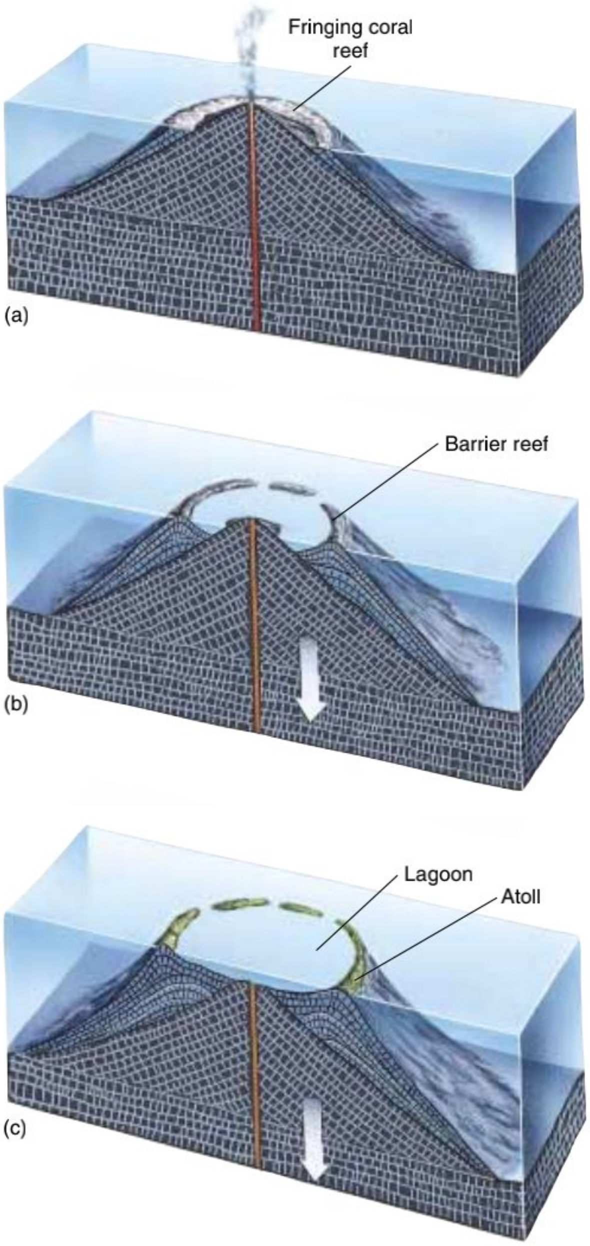



**Figure 18–11** (a) When a volcanic island is rising or static, the reef remains attached to the beach and is called a fringing reef. (b) As the island sinks, the reef continues to grow upward to form a barrier reef. (c) Finally the island becomes submerged and the reef forms a circular atoll.

in the deep sea? Charles Darwin studied this question during his famous voyage on the *Beagle* from 1831 to 1836. He reasoned that a coral reef must have formed in shallow water on the flanks of a volcanic island. Eventually the island sank, but the reef continued to grow upward, so that the living portion always remained in shallow water (Fig. 18–11). This proposal was not accepted at first because scientists could not explain how a volcanic island could sink. However, when scientists drilled into a Pacific atoll shortly after World War II and found volcanic rock hundreds of meters beneath the reef, Darwin's original hypothesis was reconsidered. Today we know that the weight of a volcano causes the lithosphere to sink. In addition, the hot lithosphere beneath a volcanic island cools after the volcano becomes extinct. As a result, it becomes denser and contracts, adding to the sinking effect.

Reefs around the world have suffered severe epidemics of disease and predation within the last decade. Studies of fossils show that epidemics and mass extinctions have affected reefs periodically for hundreds of millions of years. However, some oceanographers have suggested that human activity has provoked the recent epidemics. One suggested cause is that sewage provides nutrients for algae and other organisms that smother reef organisms. Another is that chemical pollutants are altering the species balance in aquatic ecosystems. A third is that seawater temperature has risen in response to global warming and that reef organisms are adversely affected by warmer seawater.

## 18.3 EMERGENT AND SUBMERGENT COASTLINES

Geologists have found drowned river valleys and fossils of land animals on continental shelves beneath the sea. They have also found fossils of fish and other marine organisms in continental interiors. As a result, we infer that sea level has changed, sometimes dramatically, throughout geologic time. An **emergent coastline** forms when a portion of a continent that was previously under water becomes exposed as dry land. Falling sea level or rising land can cause emergence. In contrast, a **submergent coastline** develops when the sea floods low-lying land and the shoreline moves inland (Fig. 18–12). Submergence occurs when sea level rises or coastal land sinks.

### FACTORS THAT CAUSE COASTAL EMERGENCE AND SUBMERGENCE

Tectonic processes, such as mountain building or basin formation, can cause a coastline to rise or sink. Isostatic adjustment can also depress or elevate a portion of a coastline. About 18,000 years ago, a huge continental glacier covered most of Scandinavia, causing it to sink isostatically. As the crust settled, the displaced asthenosphere flowed southward, causing the Netherlands to rise. When the ice melted, the process reversed. Today, Scandinavia is rebounding and the Netherlands is sinking. These tectonic and isostatic processes cause local or

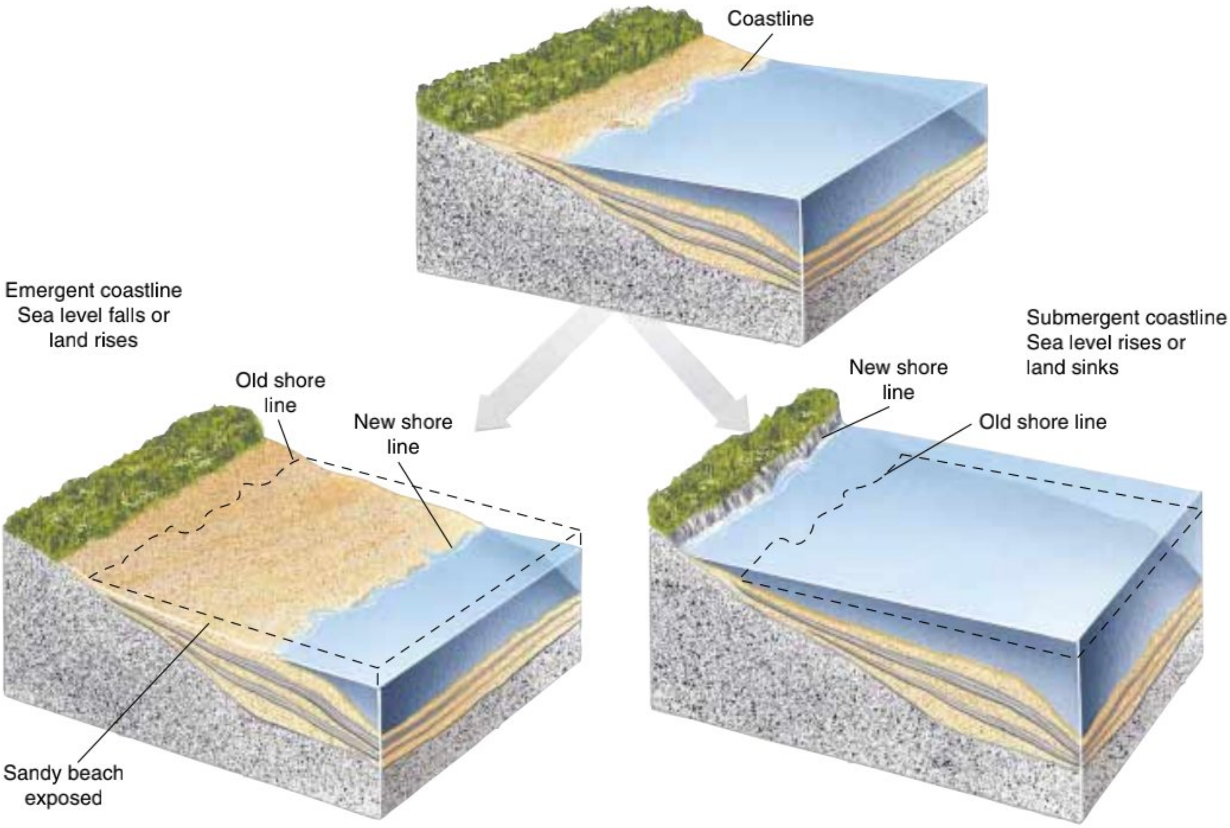



**Figure 18–12** Emergent and submergent coastlines. If sea level falls or if the land rises, offshore sand is exposed to form a sandy beach. If coastal land sinks or sea level rises, areas that were once land are flooded. Irregular shorelines develop and beaches are commonly sediment poor.

regional sea level changes but do not affect global sea level.

Sea level can also change globally. A global sea-level change, called **eustatic change**, occurs by three mechanisms: changes in water temperature, changes in the volume of the mid-oceanic ridge, and growth and melting of glaciers.

Water expands or contracts when its temperature changes. Although this change is not noticeable in a glass of water, the volume of the oceans is so great that a small temperature change can alter sea level measurably. Water is most dense at 4°C. Because most temperate and tropical oceans are warmer than 4°C, most ocean water expands when warmed and contracts when cooled. Thus, global warming causes a sea-level rise and cooling leads to falling sea level.

As explained in Chapter 11, changes in the volume of the mid-oceanic ridge can also affect sea level. The mid-oceanic ridge displaces seawater. When lithospheric plates spread slowly from the mid-oceanic ridge, the new lithosphere cools and shrinks before it travels far. Thus, slow sea-floor spreading creates a narrow ridge that displaces relatively small amounts of seawater and leads to low sea level. In contrast, rapidly spreading plates produce a high-volume ridge, causing a global sea-level rise just as the water level in the bathtub rises when you settle into a bath. At times in Earth history, spreading has been relatively rapid, and as a result, global sea level has been high.

During an ice age, vast amounts of water move from the sea to continental glaciers, and sea level falls globally, resulting in emergence. At the same time, the weight of a glacier can isostatically depress a coastline, causing local or regional submergence. Similarly, when glaciers melt, sea level rises globally, causing submergence, but the melting ice allows the unburdened continent to rise isostatically, resulting in local or regional emergence. The net result along any particular coast is determined by the balance between global sea-level change and the local or regional isostatic adjustments.

Temperature changes and glaciation are linked. When global temperature rises, seawater expands and glaciers melt; when temperature falls, seawater contracts and glaciers grow.

## 18.4 SANDY AND ROCKY COASTLINES

Coastal weathering and erosion occur by many processes (Fig. 18–13). Waves hurl sand and gravel against sea cliffs, wearing them away. Salt water dissolves soluble minerals. Salt water also soaks into cracks in the bedrock; when the water evaporates, the growing salt crystals pry the rock apart. In addition, when a wave strikes fractured rock, it compresses air in the cracks. This compressed air can enlarge the cracks and dislodge rocks. Storm waves create forces as great as 25 to 30 tons per square meter and can dislodge and lift large boulders. Engineers built a breakwater of house-sized rocks weighing 80 to 100 tons each in Wick Bay, Scotland. The rocks were bound together with steel rods set in concrete and topped by a steel-reinforced concrete cap weighing over 800 tons. One large storm broke the cap and scattered the rocks. On the Oregon coast, waves tossed a 60-kilogram rock over a 25-meter-high lighthouse. The rock then crashed through the roof of the keeper's cottage, startling the inhabitants.

If weathering and erosion occur along all coastlines, why are some beaches sandy and others rocky? The answer is that most coastal sediment is not formed by weathering and erosion at the beach itself, but is transported from other places. Major rivers carry large quantities of sand, silt, and clay to the sea and deposit it on deltas that may cover thousands of square kilometers. In some coastal regions, waves and currents erode sediment from glacial till that was deposited along coastlines during the Pleistocene Ice Age. In some tropical regions, eroding reefs supply sediment. Sandy coastlines occur where sediment from any of these sources is abundant; rocky coastlines occur where sediment is scarce.

### SANDY COASTLINES

Most of the sand along coasts accumulates in shallow water offshore from the beach. If a coastline rises or sea level falls, this vast supply of sand is exposed. Thus, sandy beaches are abundant on emergent coastlines.

Longshore currents and waves erode, transport, and deposit sand along a coast. Much of the sand found at Cape Hatteras, North Carolina, originated from the mouth of the Hudson River and from glacial deposits on Long Island and southern New England. Midway along this coast, at Sandy Hook, New Jersey, an average of 2000 tons a day move along the beach. As a result of this process, beaches have been called "rivers of sand."

A long ridge of sand or gravel extending out from a beach is called a **spit** (Fig. 18–14). A spit may block the

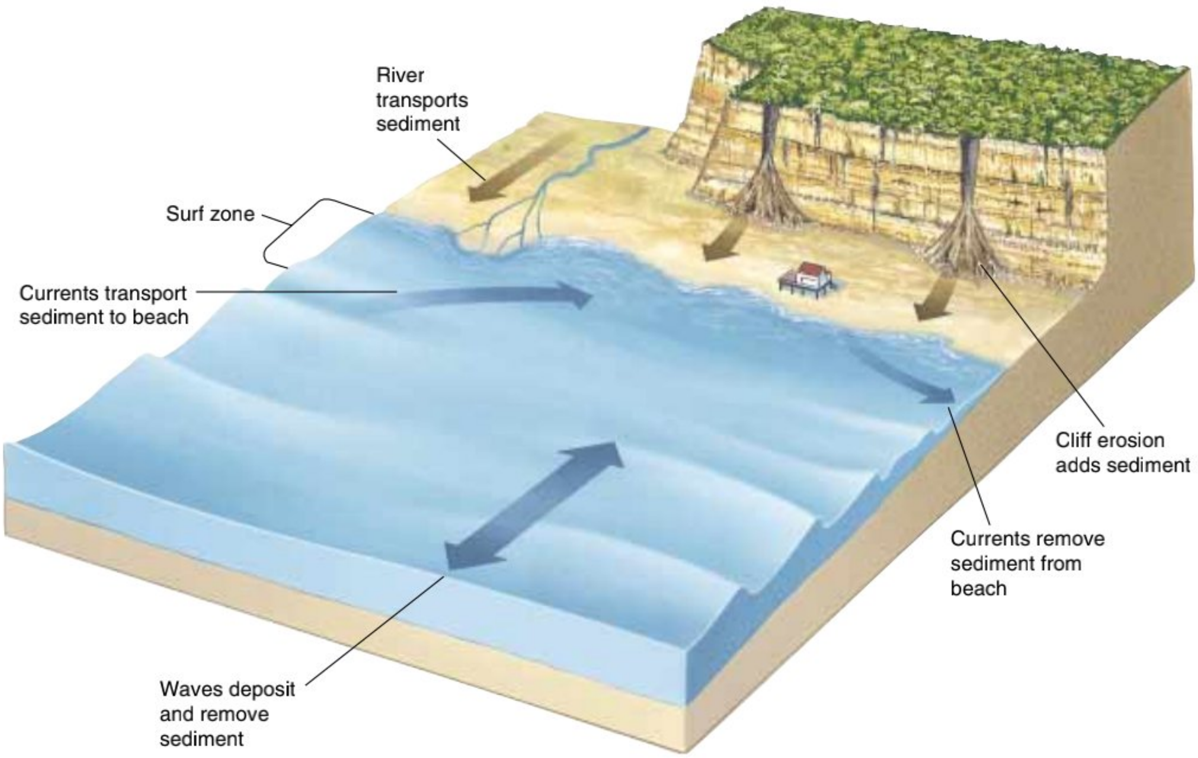
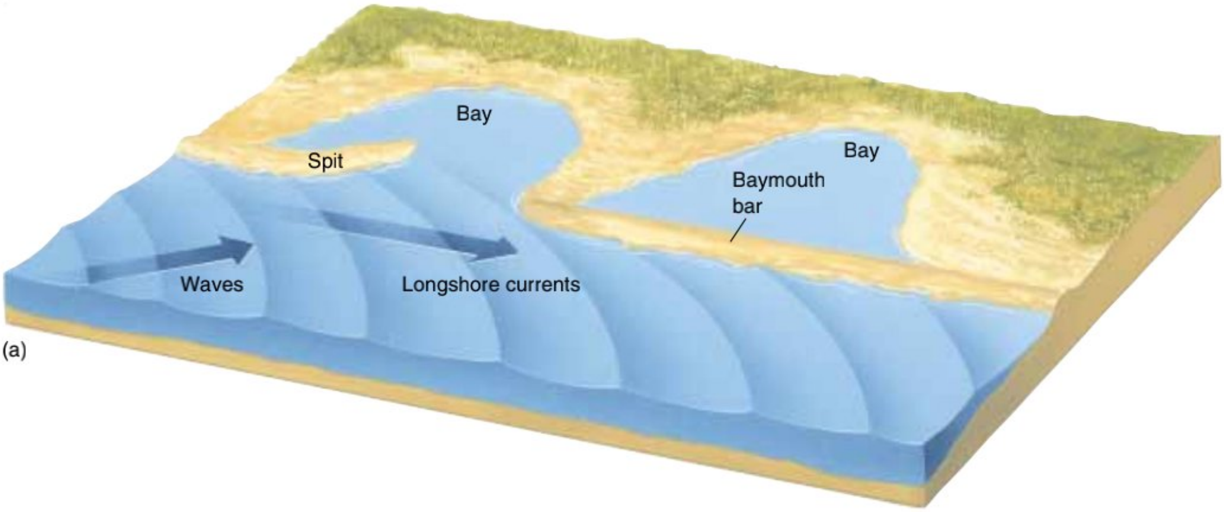



**Figure 18–13** The growth and shrinkage of a beach depend on the sum total of erosion and deposition.




(a)

(b)

**Figure 18–14** (a) A spit forms where sediment is carried away from the shore and deposited. If a spit closes the mouth of a bay, it becomes a baymouth bar. (b) Aerial view of a spit that formed along a low-lying coast in northern Siberia.

entrance to a bay, forming a **baymouth bar**. A spit may also extend outward into the sea, creating a trap for other moving sediment. A well-developed spit may be several meters above high tide level and tens of kilometers long.

A **barrier island** is a long, low-lying island that extends parallel to the shoreline. It looks like a beach or spit and is separated from the mainland by a sheltered body of water called a **lagoon** (Fig. 18–15). Barrier islands extend along the east coast of the United States from New York to Florida. They are so nearly continuous that a sailor in a small boat or a kayak can navigate the entire coast inside the barrier island system and remain protected from the open ocean most of the time. Barrier islands also line the Texas Gulf Coast.

Barrier islands form in several ways. The two essential ingredients are a large supply of sand and waves or currents to transport it. If a coast is shallow for several kilometers outward from shore, breaking storm waves may carry sand toward shore and deposit it just offshore as a barrier island. Alternatively, if a longshore current veers out to sea, it slows down and deposits sand where it reaches deeper water. Waves may then pile up the sand to form a barrier island. Other mechanisms involve sea-level change. Underwater sand bars may be exposed as a coastline emerges. Alternatively, sand dunes or beaches may form barrier islands if a coastline sinks.

Many seaside resorts are built on spits and barrier islands, and developers often ignore the fact that these are transient and changing landforms. If the rate of erosion exceeds that of deposition for a few years in a row, a spit or barrier island can shrink or disappear completely, leading to destruction of beach homes and resorts. In ad-

**Figure 18–15** An aerial view of a barrier island along the south coast of Long Island. The sheltered lagoon is on the left side of the island.

dition, barrier islands are especially vulnerable to hurricanes, which can wash over low-lying islands and move enormous amounts of sediment in a very brief time.

## ROCKY COASTLINES

In contrast to the sandy beaches typical of emergent coastlines, submergent coastlines are commonly sediment poor and are characterized by steep, rocky shores. In many areas on land, bedrock is exposed or covered by a thin layer of soil. If this type of sediment-poor terrain is submerged, and if rivers do not supply large amounts of sand, the coastline is rocky.

A submergent coast is commonly irregular, with many bays and headlands. The coast of Maine, with its numerous inlets and rocky bluffs, is a submergent coastline (Fig. 18–16). Small sandy beaches form in protected coves, but most of the headlands are rocky and steep.

As waves approach an irregular, rocky coast, they reach the headlands first, breaking against the rocks and eroding the cliffs. The waves then refract around the headland and break against its sides. Thus, most of the wave energy is spent on the headlands. As a result, the waves inside the adjacent bay are less energetic and deposit the sediment eroded from the headland. As the headlands erode and the interiors of bays fill with sediment, an irregular coastline eventually straightens (Fig. 18–17).

A **wave-cut cliff** forms when waves erode a rocky headland into a steep profile. As the cliff erodes, it leaves a flat or gently sloping **wave-cut platform** (Fig. 18–18). If waves cut a cave into a narrow headland, the cave may eventually erode all the way through the headland, forming a scenic **sea arch**. When an arch collapses or when the inshore part of a headland erodes faster than the tip, a pillar of rock called a **sea stack** forms (Fig. 18–19). As waves continue to batter the rock, eventually the sea stack crumbles.

**Figure 18–16** The Maine coast is a rocky, irregular, submergent coastline.

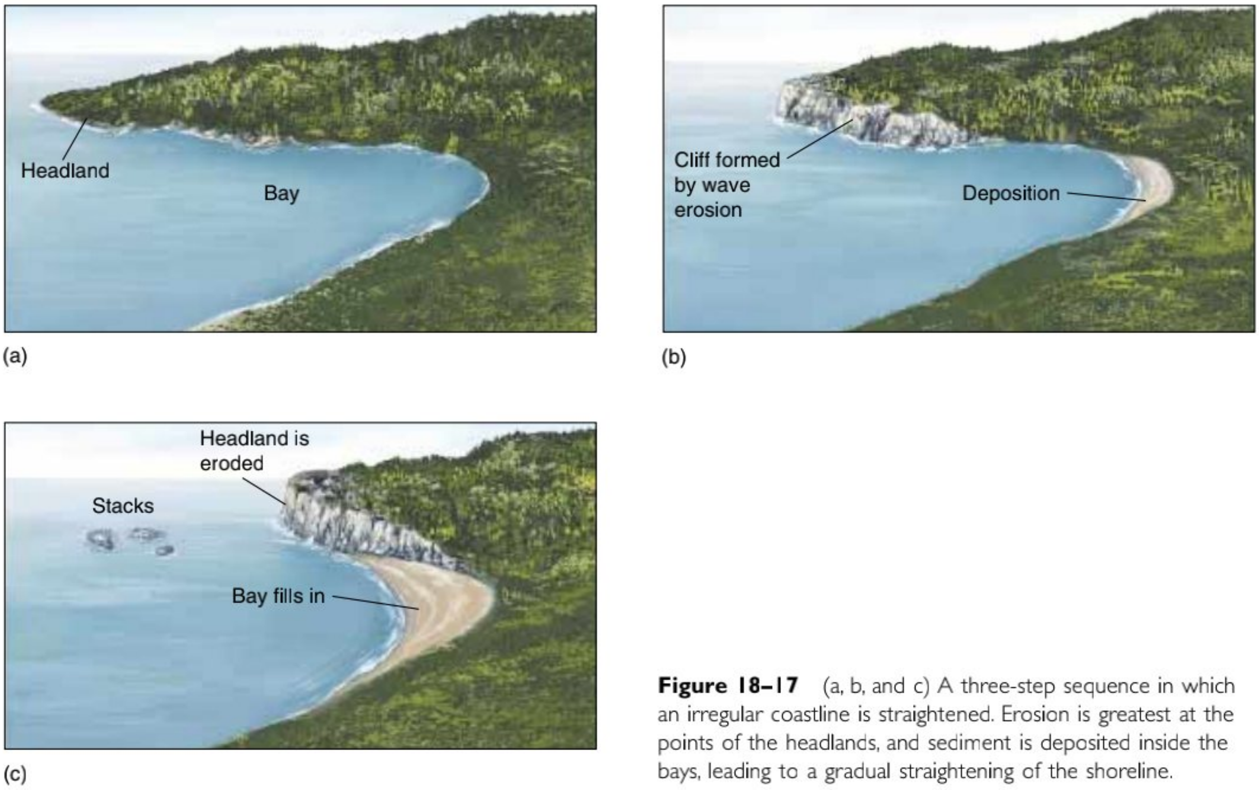



**Figure 18–17** (a, b, and c) A three-step sequence in which an irregular coastline is straightened. Erosion is greatest at the points of the headlands, and sediment is deposited inside the bays, leading to a gradual straightening of the shoreline.

If the sea floods a long, narrow, steep-sided coastal valley, a sinuous bay called a **fjord** is formed. Fjords are common at high latitudes, where rising sea level flooded glacially scoured valleys submerged as the Pleistocene glaciers melted (refer back to Fig. 17–18). Fjords may be hundreds of meters deep, and often the cliffs drop straight into the sea.

An **estuary** forms where rising sea level or a sinking coastline submerges a broad river valley or other basin. Estuaries are ordinarily shallow and have gentle, sloping beaches. Streams transport nutrients to the bay, and the shallow water provides habitats for marine organisms. Estuaries also make excellent harbors and therefore are prime sites for industrial activity. As a result, many estuaries have become seriously polluted in recent years.

**Figure 18–18** Waves hurl sand and gravel against solid rock to erode cliffs and wave-cut platforms along the Oregon coast.

**Figure 18–19** Sea stacks are common along the rocky Oregon coast.

## 18.5 DEVELOPMENT OF COASTLINES

### CASE STUDY Long Island

Long Island extends eastward from New York City and is separated from Connecticut by Long Island Sound (Fig. 18–20). Narrow, low barrier islands line the southern coast of Long Island. Longshore currents flow westward, eroding sand from glacial deposits at the eastern end of the island and carrying it past beaches and barrier islands toward New Jersey.

Over geologic time, the beaches and barrier islands of Long Island are unstable. The glacial deposits at the eastern end of the island will become exhausted and the flow of sand will cease. Then the entire coastline will erode and the barrier islands and beaches will disappear. However, this change will not occur in the near future because a vast amount of sand is still available at the eastern end of the island. Thus, the beaches are stable over a period of hundreds of years. Over this time, longshore currents move sand continuously. At any point along the beach, the currents erode and deposit sand at approximately the same rate.

If we narrow our time perspective further and look at a Long Island beach over a season or during a single storm, it may shrink or expand. Over such short times, the rates of erosion and deposition are not equal. In the winter violent waves and currents erode beaches, whereas sand accumulates on the beaches during the calmer summer months. In an effort to prevent these seasonal fluctuations and to protect their personal beaches, Long Island property owners have built stone barriers called **groins** from shore out into the water. A groin intercepts the steady flow of sand moving from the east and keeps that particular part of the beach from eroding (Fig. 18–21). But the groin impedes the overall flow of sand. West of the groin the beach erodes as usual, but the sand is not replenished because the upstream groin traps it. As a result, beaches downcurrent from the groin erode away (Fig. 18–22). The landowner living downcurrent from a groin may then decide to build another groin to protect his or her beach (Fig. 18–21c). The situation has a domino effect, with the net result that millions of dollars are spent in ultimately futile attempts to stabilize a system that was naturally stable in its own dynamic manner.

Storms pose another dilemma. Hurricanes strike Long Island in the late summer and fall, generating storm waves that completely overrun the barrier islands, flattening dunes and eroding beaches. When the storms are over, gentler waves and longshore currents carry sediment back to the beaches and rebuild them. As the sand accumulates again, salt marshes rejuvenate and the dune grasses grow back within a few months.

These short-term fluctuations are incompatible with human ambitions, however. People build houses, resorts, and hotels on or near the shifting sands. The owner of a home or resort hotel cannot allow the buildings to be flooded or washed away. Therefore, property owners construct large sea walls along the beach. When a storm wave rolls across an undeveloped low-lying beach, it dissipates its energy gradually as it flows over the dunes and transports sand. The beach is like a judo master who defeats an opponent by yielding to the attack, not countering it head on. A sea wall interrupts this gradual absorption of wave energy. The waves crash violently against the barrier and erode sediment at its base until

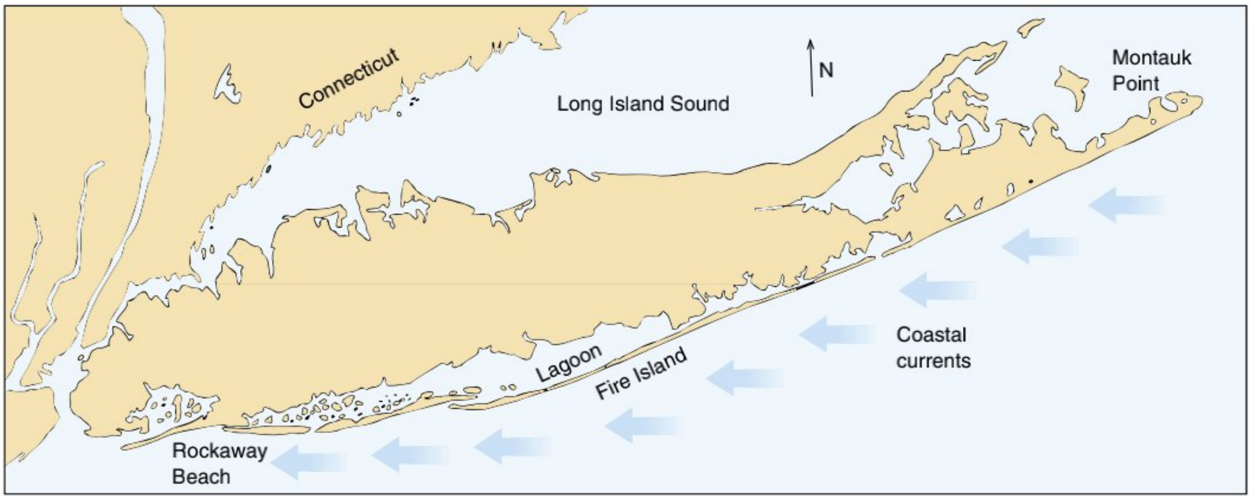



**Figure 18–20** Longshore currents carry sand westward along the south shore of Long Island.

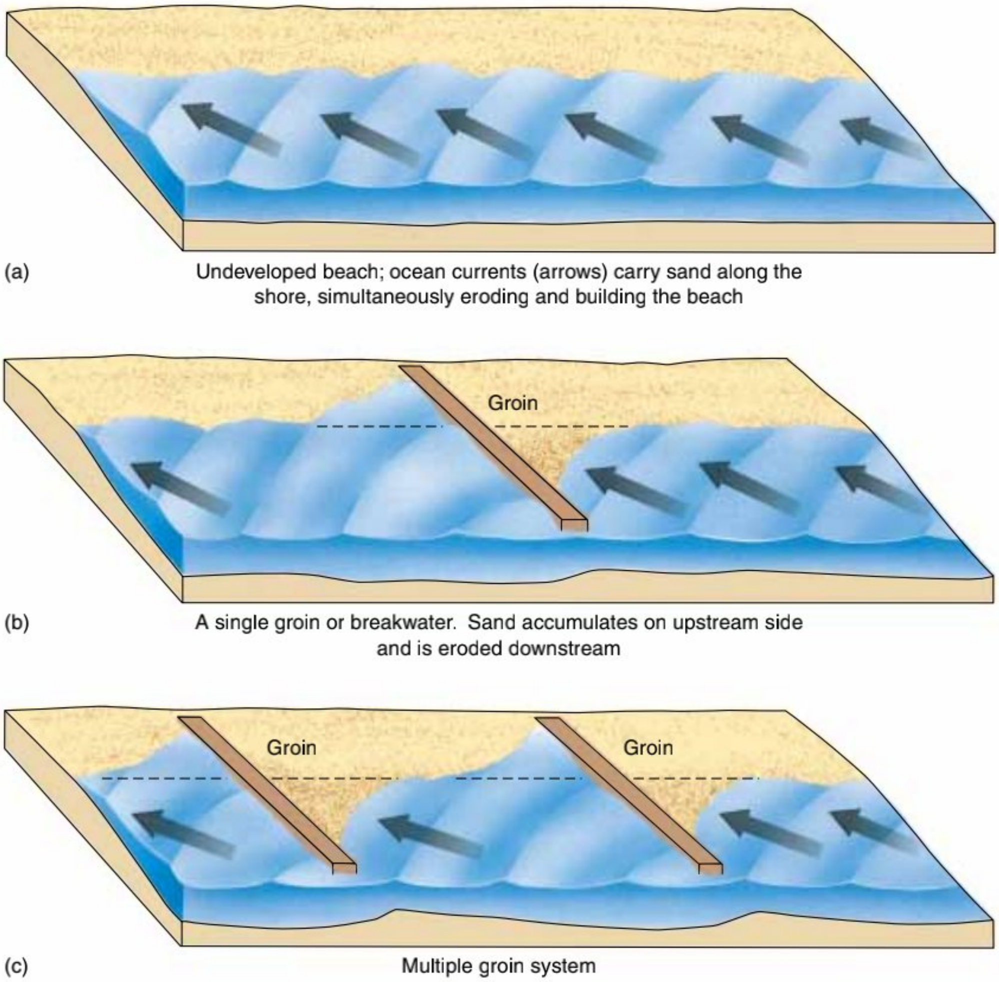



**Figure 18–21** (a) Longshore currents simultaneously erode and deposit sand along an undeveloped beach. (b) A single groin or breakwater traps sand on the upstream side, resulting in erosion on the downstream side. (c) A multiple groin system propagates the uneven distribution of sand along the entire beach.

(a) (b)

**Figure 18–22** (a) This aerial photograph of a Long Island beach shows sand accumulating on the upstream side of a groin, and erosion on the downstream side. (b) A closeup of the house in (a) shows waves lapping against the foundation.

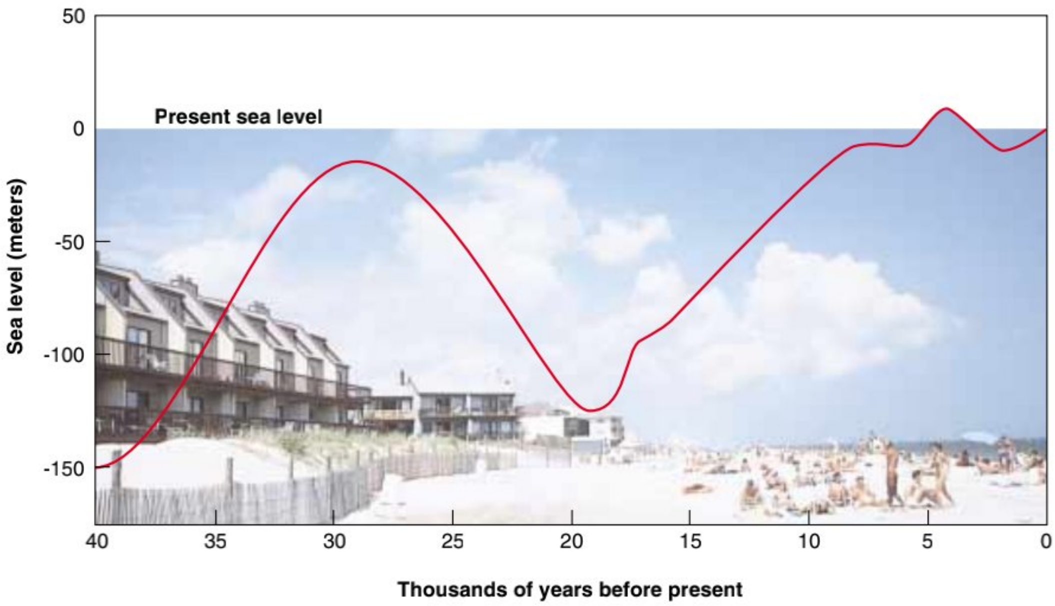



**Figure 18–23** Sea level has fluctuated more than 150 meters during the past 40,000 years. (Data from J. D. Hansom, *Coasts.* Cambridge, U.K.: Cambridge University Press, 1988)

the wall collapses. It may seem surprising that a reinforced concrete sea wall is *more* likely to be permanently destroyed than a beach of grasses and sand dunes, yet this is often the case.

## 18.6 GLOBAL WARMING AND SEA-LEVEL RISE

Sea level has risen and fallen repeatedly in the geologic past, and coastlines have emerged and submerged throughout Earth history. During the past 40,000 years, sea level has fluctuated by 150 meters, primarily in response to growth and melting of glaciers (Fig. 18–23). The rapid sea-level rise that started about 18,000 years ago began to level off about 7000 years ago. By coincidence, humans began to build cities about 7000 years ago. Thus, civilization has developed during a short time when sea level has been relatively constant.

Global sea level started rising again about 75 years ago, at a rate of about 1.5 to 2.5 millimeters per year (Fig. 18–24). The change in a single year is small, but it is half as fast as the dramatic postglacial sea-level rise. Many climatologists predict that the greenhouse effect will raise global temperature during the next century. If global warming occurs, sea level will rise because of melting polar ice sheets and expansion of seawater. Although estimates vary, many scientists predict a 1-meter rise in sea level by the year 2100.

Consequences of a 1-meter sea-level rise vary with location and economics. The wealthy, developed nations would build massive barriers to protect cities and harbors. In regions where global sea-level rise is compounded by local tectonic sinking, dikes are already in

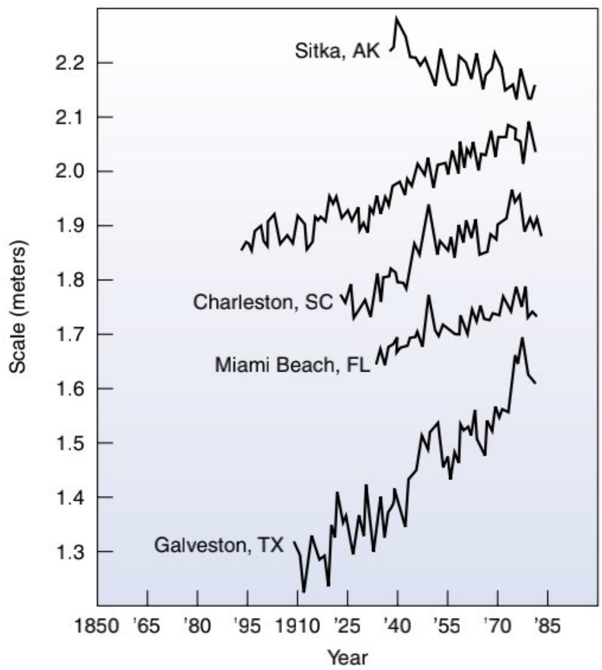



**Figure 18–24** Coastal emergence and submergence at several locations in the United States. Land subsidence in Galveston has led to rapid submergence, and tectonic uplift along the Alaskan coast has led to local emergence in Sitka. (Stephen H. Schneider, *Global Warming*, p. 164)

**Figure 18–25** A 1-meter sea-level rise would flood 17 percent of the land area of Bangladesh and displace 38 million people. (AP/Wide World Photos)

place or planned. Portions of Holland lie below sea level, and the land is protected by a massive system of dikes. In London, where the high-tide level has risen by 1 meter in the past century, multimillion-dollar storm gates have been built on the Thames River. A similar system is now planned to protect Venice from further flooding.

If sea level rises as predicted, people in the United States will spend about $10 billion per year to protect developed coastlines. The cost will exceed that of any construction project in history. Wetlands, farms, and houses that are not valuable enough to be protected will be lost. If sea level rises by 1 meter, 20,000 square kilometers of dry land and 17,000 square kilometers of coastal wetlands in the United States will be flooded. In addition, storm damage and coastal erosion will increase.

Many poor countries cannot afford coastal protection. A 1-meter rise in sea level would flood portions of the Nile delta, displacing 10 million people and decreasing Egypt's agricultural productivity by 15 percent. Seventeen percent of the land area of Bangladesh would be flooded, displacing 38 million inhabitants (Fig. 18–25).

## SUMMARY

In deep water, the size of a wave depends on (1) the wind speed, (2) the amount of time that the wind has blown, and (3) the **fetch**. The highest part of a wave is the **crest**; the lowest, the **trough**. The distance between successive crests is called the **wavelength**. **Wave height** is the vertical distance from the crest to the trough. The water in a wave moves in circular paths. When a wave nears the shore, the bottom of the wave is slowed down and the wave **breaks**, creating **surf**. **Refraction** is the bending of a wave when it strikes the shore at an oblique angle.

Surface currents are driven by wind and affect global climate. **Longshore currents** transport sediment along a shore. A **beach** is a strip of shoreline that is washed by waves and tides. Weathering produces sediment along a beach, but most coastal sediment is transported from river deltas and glacial deposits. Reefs also add sediment in certain areas.

A **reef** is a wave-resistant ridge or mound built by corals, algae, oysters, or other marine organisms. An **atoll** forms when an island, surrounded by a reef, sinks.

If land rises or sea level falls, the coastline migrates toward the open ocean and old beaches are abandoned above the sea, forming an **emergent coastline**. Emergent coastlines are sediment rich and are characterized by sandy beaches, **spits**, **baymouth bars**, and **barrier islands**. In contrast, a **submergent coastline** forms when land sinks or sea level rises. Submergent coastlines are often sediment poor. **Wave-cut cliffs**, **wave-cut platforms**, **arches**, and **stacks** are common in this environment. Irregular coastlines are straightened by erosion and deposition. **Fjords** are submerged glacial valleys. **Estuaries** are submerged river beds and flood plains.

Human intervention may upset the natural movement of coastal sediment and alter patterns of erosion and deposition on beaches. Sea level has been rising over the past century, and it may continue to rise into the next.

## KEY WORDS

**fetch** *318*
**crest** *318*
**trough** *318*
**wavelength** *318*
**wave height** *318*
**surf** *318*
**refraction** *318*
**spring tide** *320*
**neap tide** *320*
**tidal current** *321*
**rip current** *321*
**undertow** *321*
**longshore current** *321*
**beach drift** *321*
**beach** *322*
**foreshore** *322*
**backshore** *322*
**intertidal zone** *322*
**reef** *322*
**atoll** *322*
**emergent coastline** *323*
**submergent coastline** *323*
**eustatic change** *324*
**spit** *325*
**baymouth bar** *326*
**barrier island** *326*
**lagoon** *326*
**wave-cut cliff** *327*
**wave-cut platform** *327*
**sea arch** *327*
**sea stack** *327*
**fjord** *328*
**estuary** *328*
**groin** *329*

## REVIEW QUESTIONS

1. List the three factors that determine the size of a wave.
2. Draw a picture of a wave and label the crest, the trough, the wavelength, and the wave height.
3. Describe the motion of both the surface and the deeper layers of water that is disturbed by waves.
4. Explain how surf forms.
5. What is refraction? How does it affect coastal erosion?
6. Explain the differences among a mid-oceanic current, a tidal current, a rip current, a longshore current, and beach drift.
7. List four different sources of coastal sediment.
8. Discuss the most important weathering processes along a coastline.
9. What is an emergent coastline and how does it form? Are emergent coastlines sediment rich or sediment poor? Why?
10. What is a submergent coastline and how does it form? Are submergent coastlines sediment rich or sediment poor? Why?
11. Compare and contrast a beach, a barrier island, and a spit.
12. Explain how an irregular coastline is straightened by coastal processes.
13. Describe some dominant features of a sediment-poor coastline.
14. What is a groin? How does it affect the beach in its immediate vicinity? How does it affect the entire shoreline?
15. Explain how greenhouse warming could lead to a rise in sea level.

## DISCUSSION QUESTIONS

1. Earthquake waves were discussed in Chapter 10. Compare and contrast earthquake waves with water waves.
2. How can a ship survive 30-meter-high storm waves, while a house along the beach will be smashed by waves of the same size?
3. Explain why very large waves cannot strike a beach directly in shallow coastal waters.
4. During World War II, few maps existed of the underwater profile of shore lines. When planning amphibious attacks on beaches of the islands in the Pacific, Allied commanders needed to know how deep the water was adjacent to the shore. Explain how this information could be deduced from aerial photographs of breaking waves and surf.
5. Imagine that an oil spill occurred from a tanker accident. Discuss the effects of mid-ocean currents, longshore currents, storm waves, and tides on the dispersal of the oil.
6. In Section 18.4 we explained how erosion and deposition tend to smooth out an irregular coastline by eroding headlands and depositing sediment in bays. If coastlines are affected in this manner, why haven't they all been smoothed out in the 4.6-billion-year history of the Earth?
7. Prepare a three-way debate. Have one side argue that the government should support the construction of groins. Have the second side argue that the government should prohibit the construction of groins. The third position defends the argument that groins should be permitted, but not supported.
8. Prepare another debate to argue whether or not government funding should be used to repair storm damage to property on barrier islands.
9. In evaluating flood danger, hydrologists use the concept of the 100-year flood. Would a similar concept be useful in planning coastal development?