Chapter 20

COASTAL PROCESSES AND TERRAIN

COASTLINES ARE AMONG THE MOST VARIED OF ALL LANDSCAPES on the planet. This diversity of form and appearance is a result of the great variety of local geology, climate, and geomorphic processes at work along the coastlines of the world. In addition to virtually all of the internal and external processes we've discussed so far, coastlines may also be shaped by waves and local ocean currents. The result is that coastal terrain is often quite different from the landscape just a short distance inland from shore.

The coastal environment is usually dynamic, often showing changes in appearance and process from day to day or even hour to hour. Part of this dynamism is a consequence of shorelines acting as an interface of the lithosphere, hydrosphere, and atmosphere—and quite often the cryosphere and biosphere as well. As we saw in the chapters on weather and climate, bodies of water—especially the oceans—are important components of a number of key Earth systems. In addition to the ocean's role of regulating the temperature of Earth, some of the energy received from the Sun ultimately powers wind that creates currents and waves that, as we will see in this chapter, can in turn shape coastal landforms.

As you study this chapter, think about these key questions:

- **In what ways does landform development along ocean coastlines differ from that along lakeshores?**
- **How are waves generated and how do waves affect shorelines?**
- **How do changes in sea level, coastal sediment deposition, and coastal sediment transport influence shorelines?**
- **How can a changing sediment budget affect the size and shape of depositional landforms such as beaches and spits?**
- **What coastal features are seen with shorelines of submergence and emergence?**
- **How do coral features such as fringing reefs, barrier reefs, and atolls develop?**

The Impact of Waves and Currents on the Landscape

Coastal processes affect only a tiny fraction of the total area of Earth's surface, but they create a landscape that is almost totally different from any other on the planet. Generally along shorelines, waves are agents of erosion, and currents are agents of transportation and deposition. The most notable land features created by wave erosion are rocky cliffs and headlands. Depositional features along coastlines are diverse in form, but by far the most common are beaches and sandbars. Beaches along the shorelines of both oceans and lakes are sometimes the most distinctive aspect of coastal landscapes. They develop as a transition from land to water, and are usually impermanent features of the landscape—building up during times of "normal" weather and eroding or completely disappearing during storms.

Seeing Geographically

Big Sur coastline of central California. Describe the pattern the waves make as they approach this irregular coastline. What do you see that suggests that the coastal cliffs are being worn back by the waves? Does the coastline seem to be comprised all of the same resistant material? Why do you say this?

COASTAL PROCESSES

FG2, FG8

The coastlines of the world's oceans and lakes extend for hundreds of thousands of kilometers. Every conceivable variety of structure, relief, and topography can be found somewhere along these coasts. Coastlines are a dynamic and highly energetic environment, primarily because of the restless motions of the waters (Figure 20-1).

The Role of Wind in Coastal Processes

We saw in Chapter 18 that wind can be an important shaper of landforms on the continents—particularly through the deposition of sand. Along coastlines, the wind has an even greater influence on topography. As we discussed in Chapter 5, one manifestation of Earth's unequal warming by the Sun is the global pattern of pressure and wind, and it is primarily wind blowing over the surface of a body of water that generates waves and ocean currents.

The wind is not the only force causing water to move, of course. As we saw in Chapter 9, oceanic coastlines also experience daily tidal fluctuations that often move enormous quantities of water. Tectonic events, particularly earthquakes, contribute to water motion, as does volcanic activity upon occasion. Even more fundamental are long-term variations in sea or lake level caused by tectonic forces and *eustatic sea-level change* (sea-level change due to an increase or decrease in the amount of water in the world ocean). However, from the standpoint of geomorphic effects, wind is the most important cause of water movement.

Coastlines of Oceans and Lakes

The processes that shape the topography of oceanic coastlines are similar to the processes acting on lakeshores, with three important exceptions:

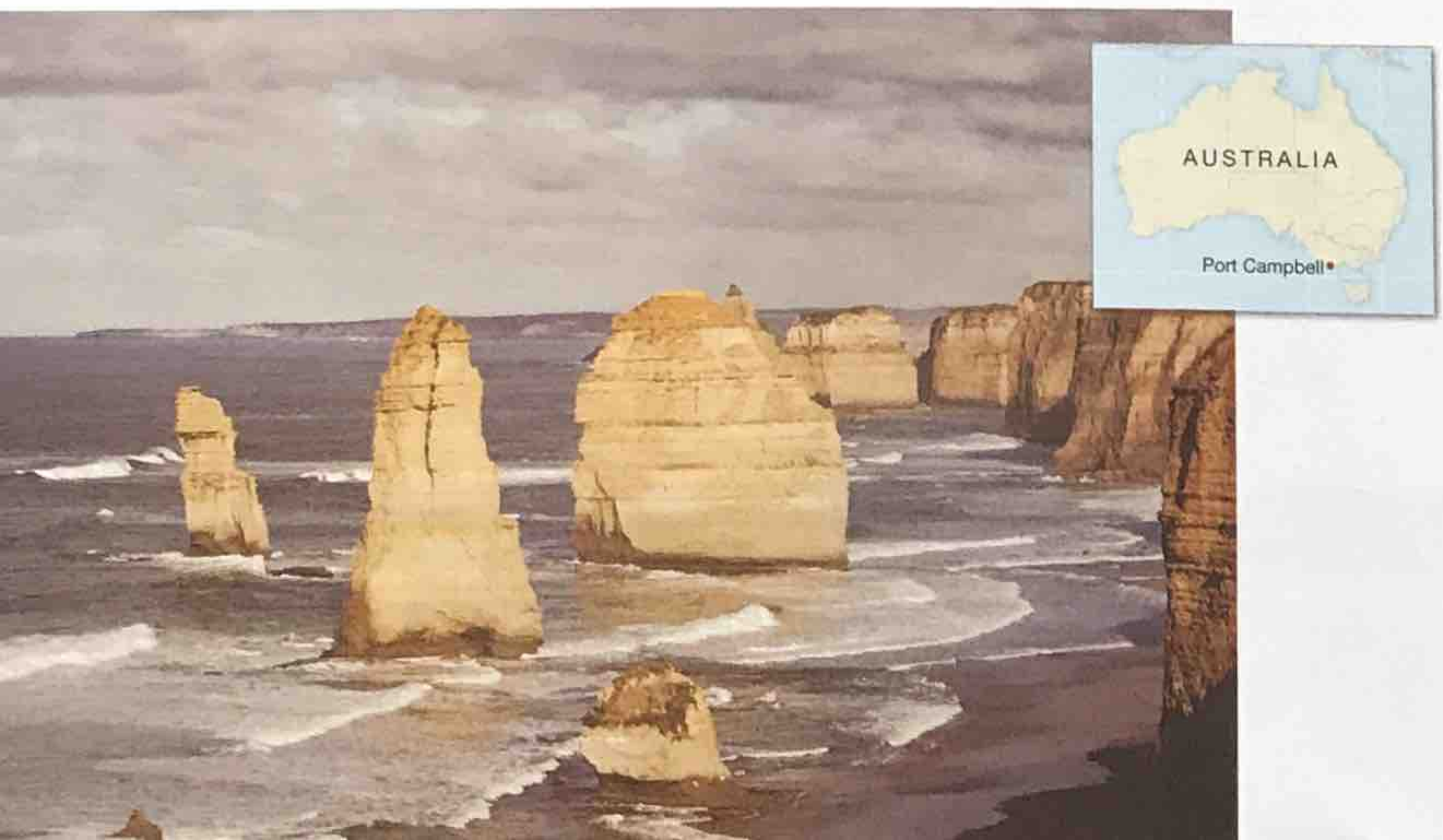
1. Along lakeshores, the range of tides is so small that they are insignificant to landform development.
2. The causes of sea-level fluctuations are quite different from the causes of lake-level fluctuations.
3. Coral reefs are built only in tropical and subtropical oceans, not in lakes.

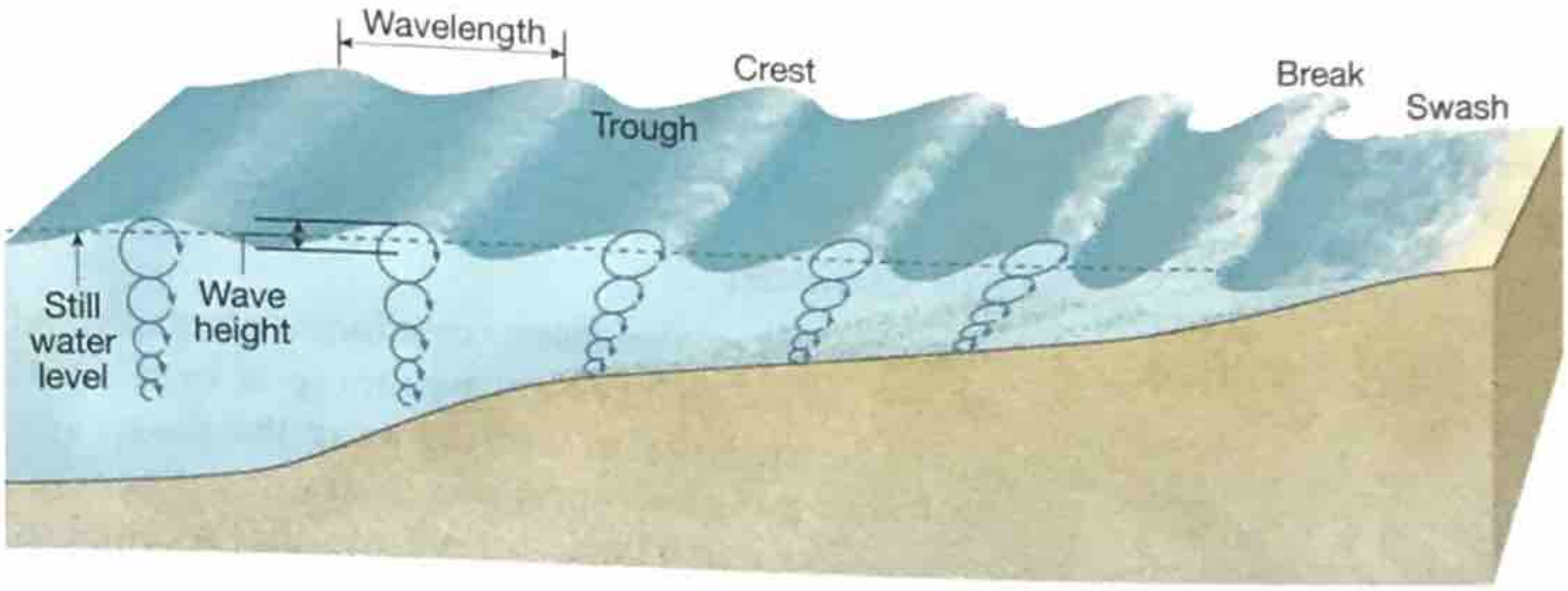
With these exceptions, the topographic forms produced on seacoasts and lakeshores are generally similar. Even so, the larger the body of water, the greater the effects of the coastal processes. Thus, topographic features developed along seacoasts are normally larger, more conspicuous, and more distinctive than those found along lakeshores, and the focus of this chapter is largely ocean shorelines.

Learning Check 20-1 In what ways are ocean shoreline-shaping processes different from those shaping lakeshores? (Answer on p. AK-6)

Many processes contribute to the shaping of coastal features. In addition to the internal and external processes discussed in earlier chapters, a number of processes largely confined to coastal areas may be at work along a shoreline, and of these, by far the most important is the work of waves, our next topic.

▾ **Figure 20-1** A coastline is the place where hydrosphere, lithosphere, and atmosphere meet. It is often an interface of ceaseless movement and energy transfer. Pounding waves do not always erode evenly and smoothly. Sea stacks and cliffs testify to the principle of differential erosion in this scene from Port Campbell National Park, Victoria, Australia.





◀ **Figure 20-2** In deep water, the passage of a wave involves almost circular movements of the water. Water movement diminishes rapidly with increasing depth, as shown here by decreasing orbital diameter downward. As the wave moves into shallow water, the revolving orbits of the water become more elliptical, the wavelength becomes shorter, and the wave becomes steeper. Eventually the wave "breaks" and dissipates its remaining energy as it washes up onto the beach.

WAVES

Waves entail the transfer of energy through a cyclical rising and falling motion in a substance. Our interest here is in water waves, which are undulations in the surface layers of a water body.

Wave Motion

Although water waves appear to move water horizontally, this appearance is misleading: in open water, the form of the wave (and therefore its energy) moves along through the water, although the water moves forward only very slightly; as we will see, this motion changes in shallow water, where waves crest and break.

Most water waves are wind generated, set in motion largely by the friction of air blowing across the water. This transfer of energy from wind to water initiates wave motion. Some water waves (called *forced waves*) are generated directly by wind stress on the water surface; they can develop to considerable size if the wind is strong, but these waves usually last for only a limited time and do not travel far. Water waves become **swells** when they travel beyond the location where they were generated by wind, and in so doing can travel enormous distances. A small number of all water waves are generated by something other than the wind, such as a tidal surge, volcanic activity, or undersea tectonic movement (discussed later in this chapter).

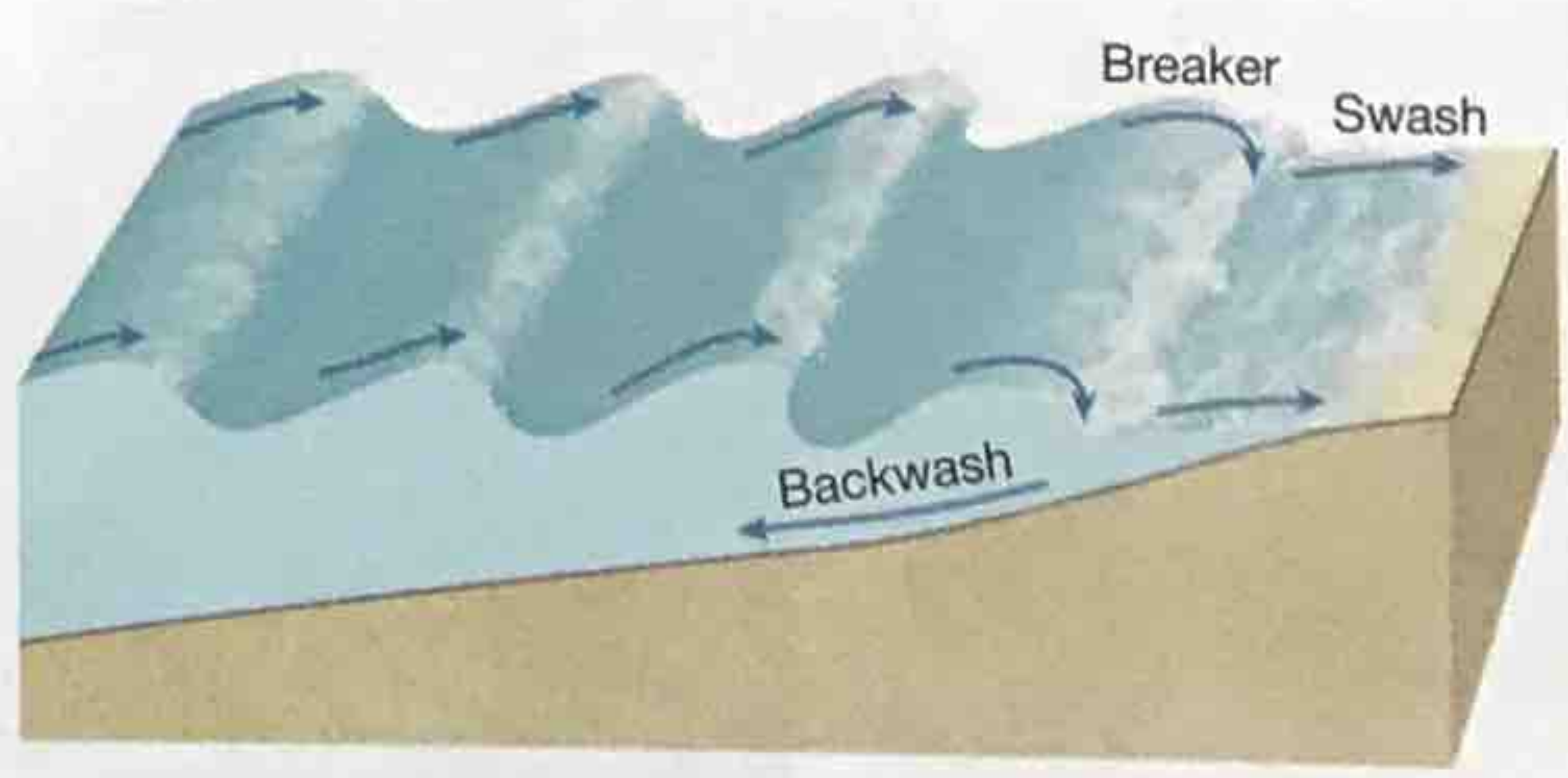
Animation
Wave Motion

Waves of Oscillation: As a wave passes a given point on the water surface, the water at that point makes a small circular or oscillatory movement, with very little forward motion (to "oscillate" means to move back and forth over the same space again and again). Waves that cause water to move this way are called **waves of oscillation**. As the wave passes, the water moves upward, producing a *wave crest*, as shown in Figure 20-2. Then crest formation is followed by a sinking of the surface that creates a *wave trough*. The horizontal distance from crest to crest or from trough to trough is called the **wavelength**. The vertical dimension of wave development is determined by the circular orbit of the surface water as the wave form passes; the vertical distance from crest to trough is equivalent to the diameter of this orbit and is called the **wave height**. The height of a wave depends on wind speed, wind duration, water depth, and *fetch* (the area of open water over which the wind blows).

The passage of a wave of oscillation normally moves water only very slightly in the direction of flow. Thus when a wave passes through an object floating on the surface simply bobs up and down without advancing, except as it may be pushed by the wind. The influence of wave movement diminishes rapidly with depth; even very high waves stir the subsurface water to a depth of only a few tens of meters.

Waves of Translation: Waves often travel great distances across deep water with relatively little change in speed or shape. As they roll into shallow water, however, a significant metamorphosis occurs. When the water depth becomes equal to about half the wavelength, the wave motion begins to be affected by frictional drag on the sea bottom. The waves of oscillation then rapidly become changed into **waves of translation**, and the result is significant horizontal movement of the surface water. Friction retards the progress of the waves so that they are slowed and bunch together, marking a decrease in wavelength, while at the same time their height is increased. As the wave moves into still shallower water, frictional drag becomes even greater and the wave becomes higher and steeper, which causes the wave to tilt forward and become more unstable. Soon and abruptly the wave *breaks* (Figure 20-3), collapsing into whitewater surf or plunging forward as a breaker or, if the height is small, perhaps simply surging up the beach without cresting.

When a wave breaks, the motion of the water instantly becomes turbulent, like that of a swift river. The breaking



▲ **Figure 20-3** A breaking wave. In shallow water the ocean bottom impedes oscillation, causing the wave to become increasingly steeper until it is so oversteepened that it collapses and tumbles forward as a breaker. The surging water then rushes up the beach as swash, and then drains off the beach below the waves as backwash.

wave rushes toward shore or up the beach as **swash**. This surge can carry sand and rock particles onto the beach, or it can pound onto rocky headlands and sea cliffs with considerable force (Figure 20-4). The momentum of the surging swash is soon overcome by friction and gravity, and a return flow, called **backwash**, drains much of the water seaward again carrying loose material with it, usually to meet the oncoming swash of the next wave.

Learning Check 20-2 **How do waves of oscillation change as they reach shallow water?**

Wave Refraction

Animation
Wave Refraction

Waves often change direction as they approach the shore, a phenomenon known as **wave refraction**. It occurs when a line of waves does not approach exactly parallel to the shore, or where the coastline is uneven or there are irregularities in water depth in the near-shore zone. For one or more of these reasons, one portion of a wave reaches shallow water sooner than other portions and is thus slowed down. This slowing down causes the wave line to bend (*refract*) as it pivots toward the obstructing area, finally breaking roughly parallel to shore. Thus, wave energy tends to be concentrated in the vicinity of an obstruction and diminished in other areas (Figure 20-5).

The most conspicuous geomorphic result of wave refraction is the focusing of wave action on headlands (Figure 20-6), subjecting them to the direct onslaught of pounding waves, whereas an adjacent bay experiences much gentler, low-energy wave action. Other things being equal (such as the resistance of the bedrock), the differential effect of wave refraction tends to smooth the coastal outline by wearing back the headlands and increasing sediment accumulation in the bays.

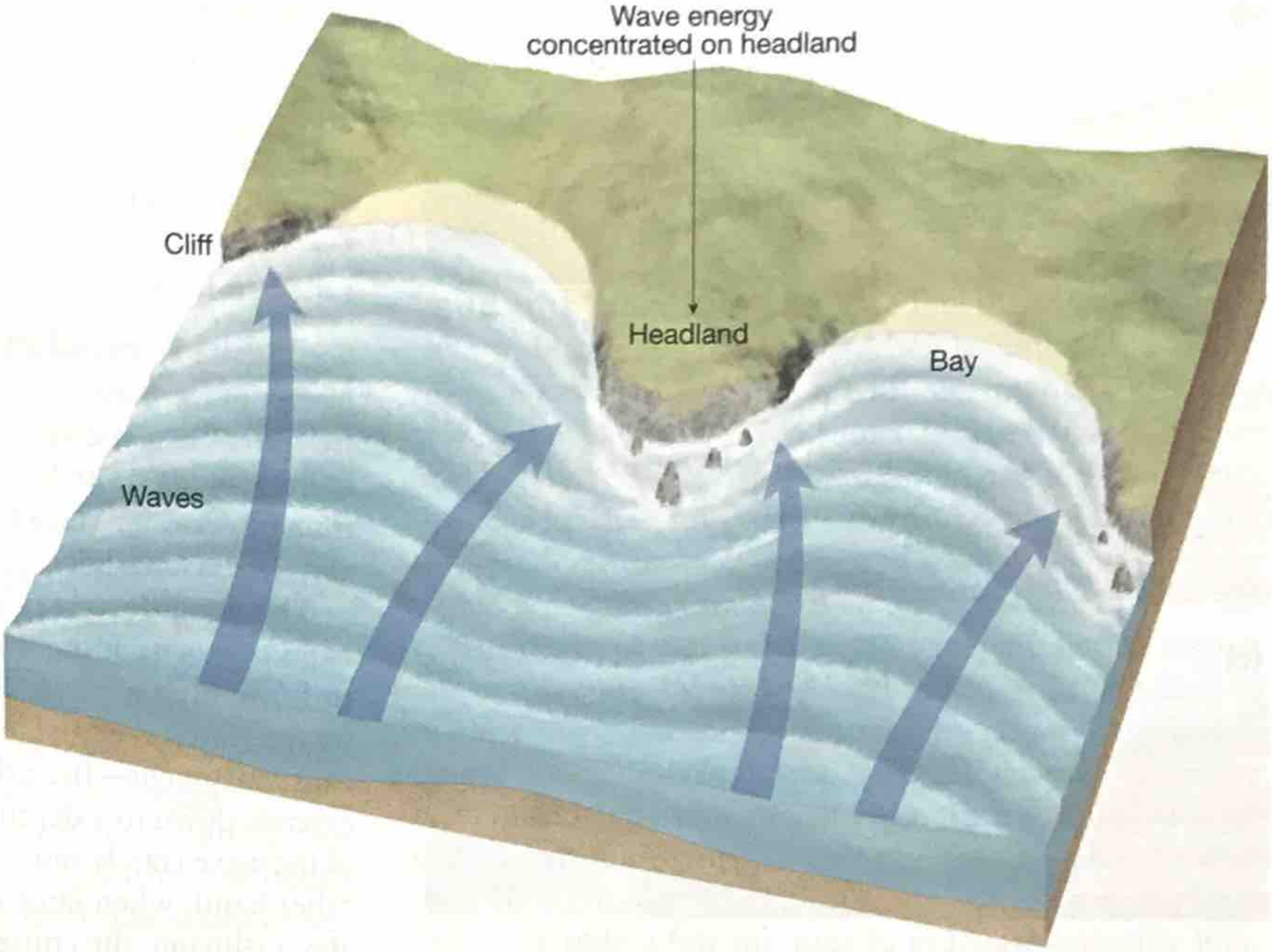
Wave Erosion

The most notable erosion along coastlines is accomplished by wave action. The incessant pounding of even small waves is a potent force in wearing away the shore, and the enormous power of storm waves almost defies comprehension—it is often large storm waves that accomplish most of the erosion along a shoreline. Waves break with abrupt and dramatic impact, hurling water, debris, and air in a thunderous crash onto the shore. Spray from breaking waves commonly moves as fast as 115 kilometers (70 miles) per hour, and small jets have been measured at more than twice that speed. This speed, coupled with the sheer mass of the water involved in such hydraulic pounding, is responsible for much coastal erosion, which is made much more effective by the abrasive rock particles carried by the waves.

Wherever the land along a shore is rocks or cliffs rather than sand, there is another dimension to wave erosion: air is forced into cracks in the rock as the wave hits the shore. The resulting compression is abruptly released as the water recedes, allowing instant expansion of the air. This pneumatic action is often very effective in loosening rock particles of various sizes.

Chemical action also plays a part in the erosion of rocks and cliffs because most rocks are to some extent soluble in seawater. In another form of weathering action, salts from seawater crystallize in the crevices and pores of onshore rocks and cliffs, and this deposition is a further mechanism for weakening and breaking up the rock (such *salt wedging* is discussed in Chapter 15).

▶ **Figure 20-4** The continuous pounding of waves can erode even the most resistant coastal rocks. This scene is Cape Kiwanda State Natural Area along the Oregon coast.

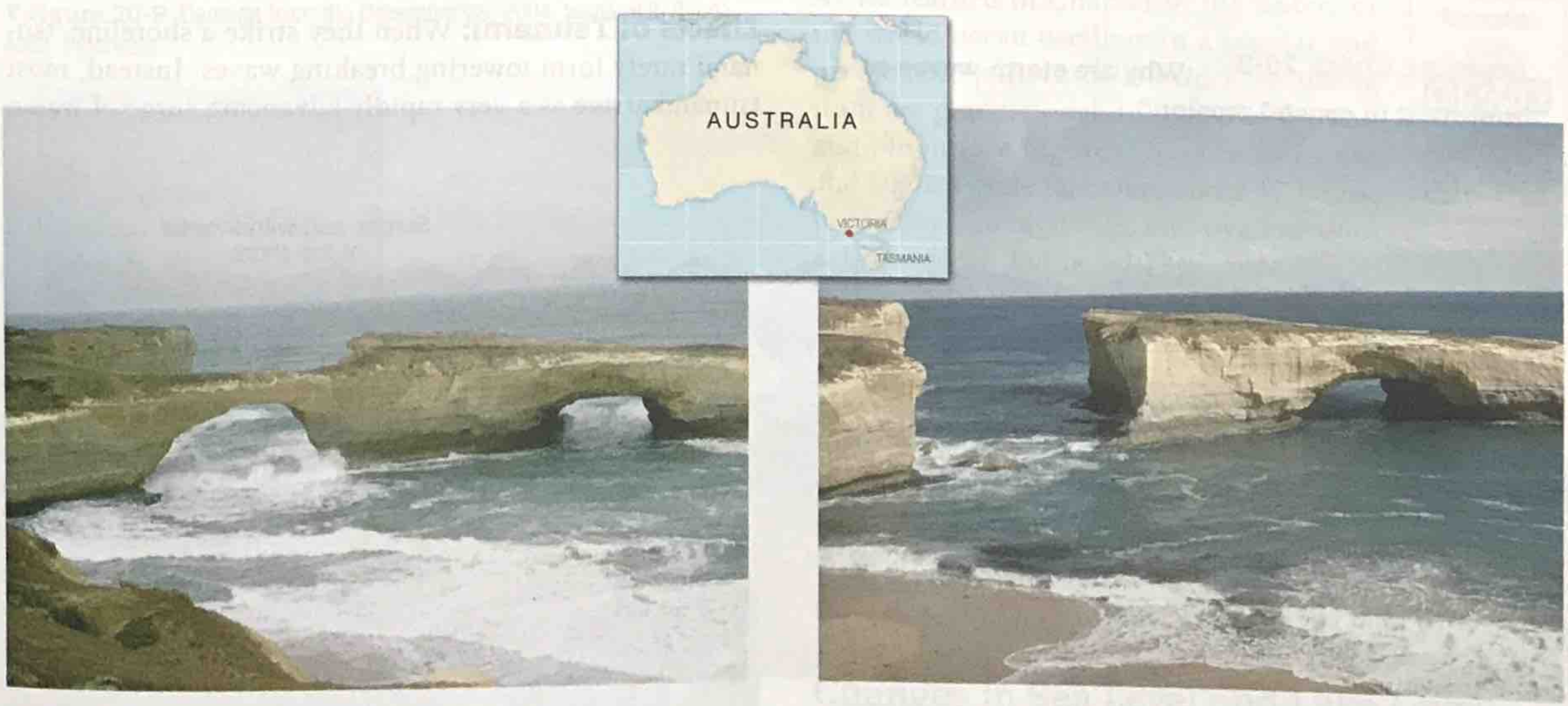


▶ **Figure 20-5** Refraction of waves on an irregular coastline. The waves reach the headland first and then "wrap" around it, breaking nearly parallel to the coastline as a result of wave refraction. Thus, wave energy is concentrated on the headlands and is diminished in the bays.

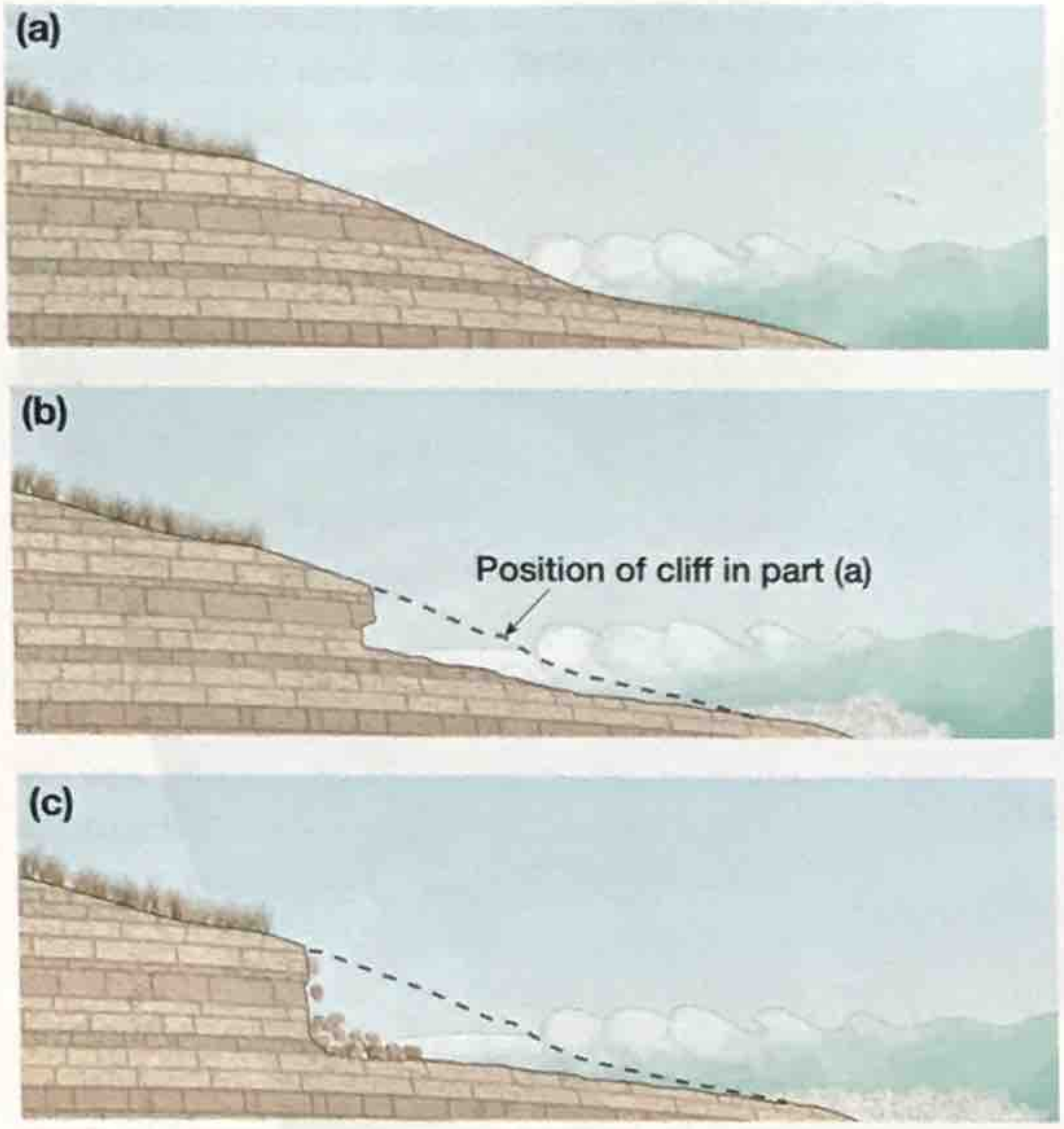
On shorelines made up of cliffs, the most effective erosion takes place just at or slightly above sea level, so that a notch is cut in the base of the cliff. The cliff face then retreats as the slope above the undercutting collapses (Figure 20-7). The resulting debris is broken, smoothed, and made smaller by further wave action, and eventually most of it is carried seaward.

As we will see later in this chapter, where a shoreline is composed of sand or other unconsolidated material, currents and tides may also cause rapid erosion. Storms greatly accelerate the erosion of sandy shores; a violent storm can remove an entire beach in just a few hours, cutting it right down to bedrock.

Whether they are awesome storm waves or mild swells, the peculiar contradiction of water waves is that they normally pass harmlessly under such fragile things as boats or swimmers in open water but can wreak



▲ **Figure 20-6** The incessant pounding of waves on this soft-rock headland on the southern coast of the state of Victoria, Australia, produced a double arch that eventually eroded into a single arch. The double-arch photograph was taken in 1985 and the single-arch one in 1992. The view is in Port Campbell National Park.



▲ **Figure 20-7** (a) Waves pounding an exposed rocky shoreline erode the rock most effectively at water level, with the result that a notch may be cut in the face of the headland. (b) The presence of this notch undermines the higher portion of the headland, which may subsequently collapse, producing a steep cliff. (c) The notching/undercutting/collapse sequence may be repeated many times, causing the cliff face to retreat.

devastation on even the hardest rocks of a shoreline. In other words, a wave of oscillation is a relatively gentle phenomenon, but a wave of translation can be a powerful force of destruction.

Learning Check 20-3 **Why are storm waves so important in coastal erosion?**

Tsunami

Animation
Tsunami

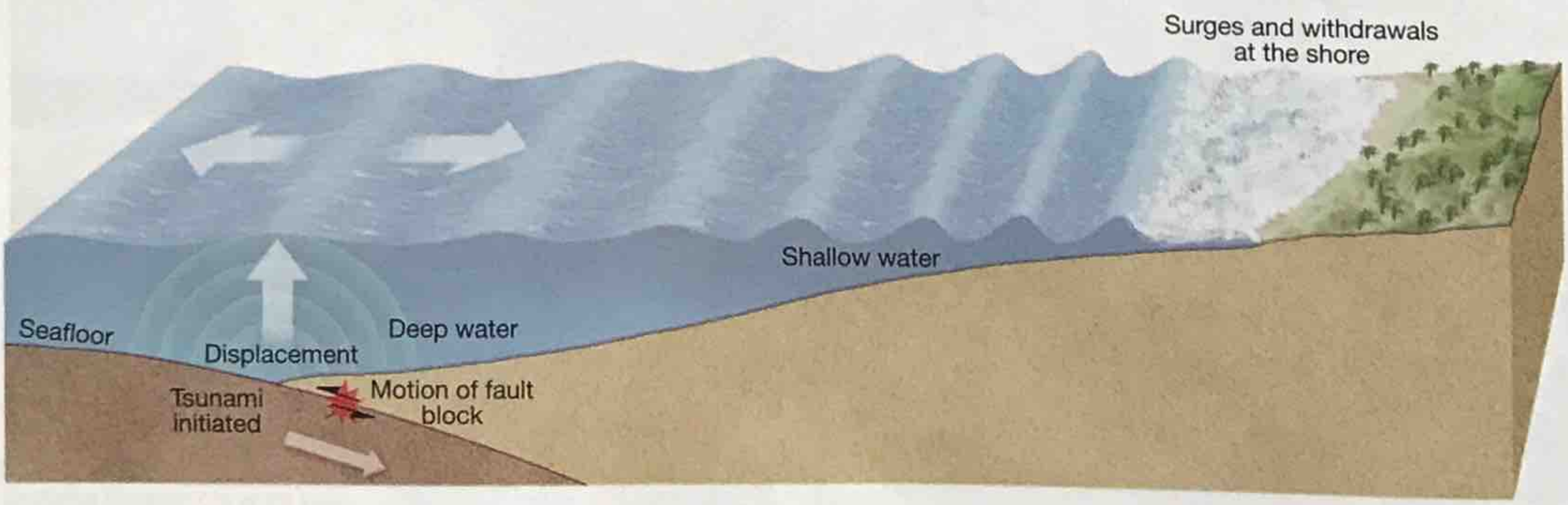
Occasionally, major oceanic wave systems are triggered by a sudden disruption of the ocean floor. These waves are called **tsunami** (from the Japanese *tsu* for "harbor" and *nami* for "wave") or *seismic sea waves* (improperly called "tidal waves").

Tsunami Formation: Most tsunami are a consequence of abrupt movement along an ocean floor fault—especially from the vertical displacement caused by reverse or thrust faulting along a subduction zone. Tsunami may also result from underwater volcanic eruptions and major underwater and coastal landslides.

The great destructive power unleashed by some tsunami comes from the way in which the ocean is disrupted to form such a wave. Recall that with wind-generated waves, only the surface of the ocean exhibits significant movement—the orbital movement of the water only extends down to a depth of about one-half the wavelength of the wave (rarely more than a few tens of meters). On the other hand, when fault rupture on the ocean floor generates a tsunami, the entire water column—from the floor of the ocean to the surface—is disrupted, displacing an enormous volume of water (Figure 20-8).

Out in the open ocean, tsunami are usually quite inconspicuous because they are low and have very long wavelengths (in the open sea a tsunami might have a wave height of only 0.5 meter [1.5 feet] with a wavelength of perhaps 200 kilometers [125 miles]), although they can travel at speeds exceeding 700 kilometers an hour (435 miles per hour). When a tsunami reaches shallow water, however, it changes considerably. As a tsunami approaches a coast, it slows—as do all waves—causing the wavelength to decrease and the wave height to increase.

Effects of Tsunami: When they strike a shoreline, tsunami rarely form towering breaking waves. Instead, most tsunami arrive as a very rapidly advancing surge of water,



▲ **Figure 20-8** The formation of a tsunami. A vertical disruption of the ocean floor, such as from faulting, displaces the entire water column from the ocean floor to the surface. In the open ocean, the tsunami may be almost indistinguishable because of its great wavelength. Once it reaches shallow water, however, wave height increases and the tsunami comes onshore as a series of surges and withdrawals.

sometimes up to 40 meters (130 feet) high. Unlike many large wind-generated waves, however, immediately behind the wave crest of a tsunami is an enormous volume of water that can surge great distances inland before receding. In many cases, before a tsunami arrives, the water withdraws from the coast, appearing like a very sudden, very low tide—this happens when the trough of the tsunami arrives. Unfortunately, people sometimes venture out on the freshly exposed subtidal areas to collect shellfish or stranded fish, only to be caught a few minutes later by the rapid surge of water when the crest of the tsunami comes onshore. Frequently, there is a series of surges and withdrawals, with the largest surge not necessarily the first to arrive.

The Sumatra–Andaman Earthquake and Tsunami of 2004: On December 26, 2004, one of the greatest natural disasters in recent history was triggered after a magnitude 9.2 earthquake shook the northern coast of Sumatra in Indonesia. A 1200 kilometer- (750 mile-) long section of the interplate thrust fault (or "megathrust"), formed where the Indo–Australian Plate is subducting beneath the Burma Plate, ruptured, uplifting the ocean floor by as much as 4.9 meters (16 feet). The sharp movement of the ocean floor generated a tsunami that spread away in all directions.

About 28 minutes after the earthquake struck, a 24-meter- (80-foot-) high wave rushed onshore at the city of Banda Aceh on the northern tip Sumatra, Indonesia, just 100 kilometers (60 miles) from the epicenter of the earthquake (Figure 20-9). The tsunami spread across the Indian Ocean, striking Sri Lanka, the Maldives Islands, and the coast of Somalia in northeast Africa. The exact death toll will likely never be known, but estimates now suggest that nearly 227,000 people died and many tens of thousands more were seriously injured. In a few locations, entire villages were quite literally washed away.

Figure 20-9 Damage from the December 26, 2004, tsunami in Banda Aceh, Indonesia.

Learning Check 20-4 **Why are tsunami often so much more destructive than even very large storm waves?**

Tsunami Warnings: Because most tsunami originate from sudden fault displacement in a subduction zone, the resulting earthquakes are readily detectable by seismographs. For decades, the Pacific Tsunami Warning Center in Hawaiʻi has used seismographic and other data to detect tsunami heading for coastlines around the Pacific basin. With such information, a tsunami warning can usually be issued long enough in advance to allow time for evacuation of the impact area. However, as the Sumatra tsunami disaster of 2004 revealed, if local warning systems are not in place, there may be no way to get evacuation orders to coastal populations in time. Further, as we saw in Sumatra in 2004 and in Japan in March 2011, if a large tsunami-generating earthquake originates close to a populated coastline, the waves can arrive so quickly that coastal residents may have only a few minutes to evacuate—see the box, "People and the Environment: The 2011 Japan Earthquake and Tsunami."

IMPORTANT SHORELINE-SHAPING PROCESSES

In addition to wind-generated waves and tsunami, a variety of other processes also modify coastlines in ways that range from gradual and subtle, to sudden and spectacular.

Tides

Animation
Tides

As we learned in Chapter 9, the waters of the world ocean oscillate in a regular and predictable pattern called *tides*, resulting from the gravitational influence of the Sun and Moon (see Figure 9-8). The tides rise and fall in a cycle that takes about 12 hours, producing two high tides and two low tides a day on most (but not all) seacoasts.

Despite the enormous amount of water moved by tides and despite the frequency of this movement, the topographic effects are surprisingly small. Tides are significant agents of erosion only in narrow bays, around the margin of shallow seas, and in passages between islands, where they produce currents strong enough to scour the bottom and erode cliffs and shorelines (Figure 20-10). The movement of water through tides is, however, a promising source of power for generating electricity—see the box, "Energy for the 21st Century: Tidal Power."

Changes in Sea Level and Lake Level

Sea-level changes can result either from the uplift or sinking of a landmass (tectonic cause), or from an increase or decrease in the amount of water in the oceans—**eustatic**

PEOPLE AND THE ENVIRONMENT

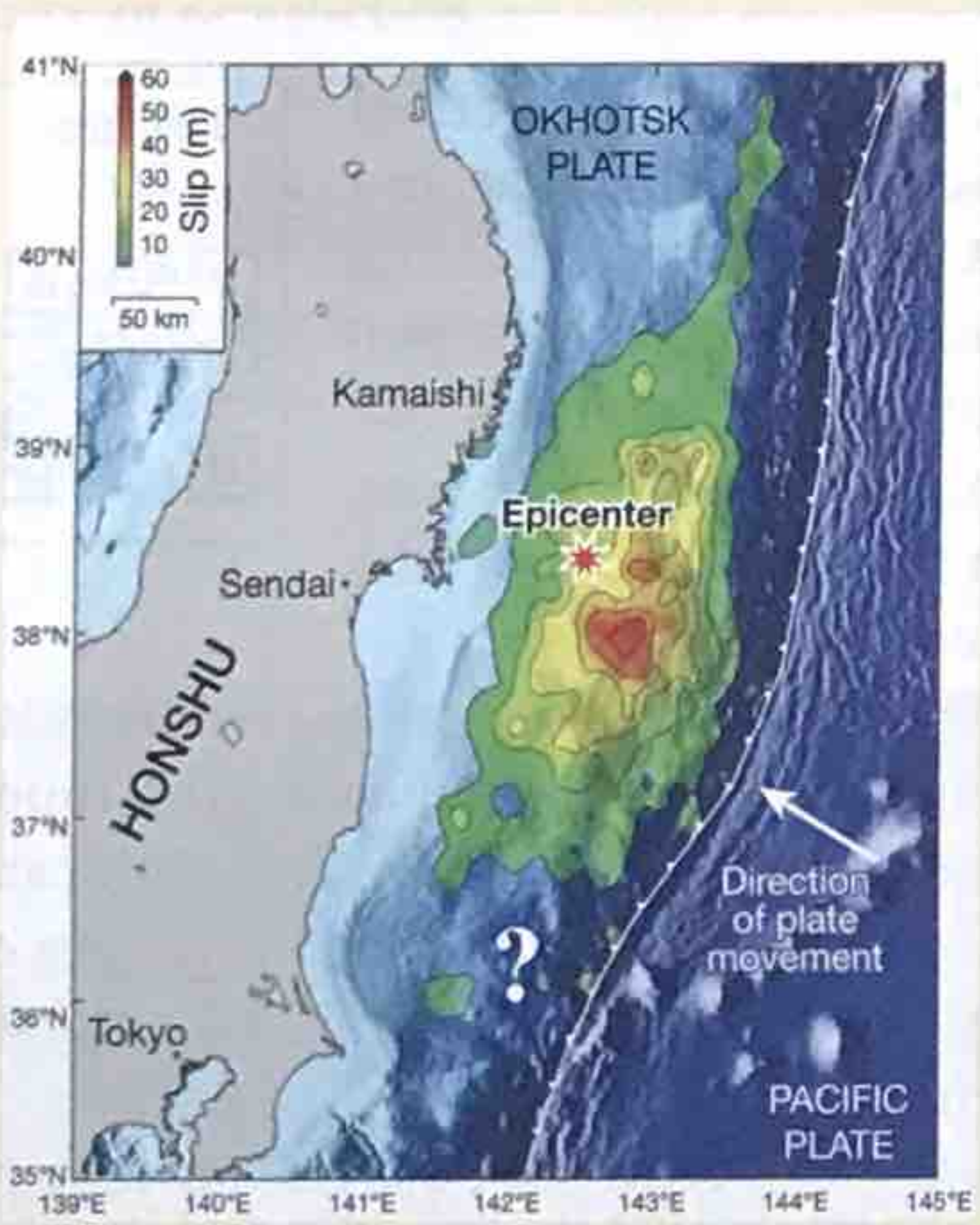
The 2011 Japan Earthquake and Tsunami

On the afternoon of March 11, 2011, a magnitude 9.0 earthquake struck the northeast coast of Honshu, the largest island of Japan. The result of the Great Tohoku Earthquake was devastation and loss of life almost unimaginable in a country that is as well prepared for large earthquakes as any in the world.

More than 15,000 people lost their lives, with many hundreds of other victims still missing. Initially, more than 130,000 people were left homeless; more than 300,000 buildings were destroyed; telecommunications, transportation, and water supplies were widely disrupted. Utilities were damaged, most dramatically when several nuclear reactors were damaged near Fukushima.

The Earthquake: The earthquake was caused by the sudden rupture and movement along a thrust fault where the Pacific Plate subducts beneath the Okhotsk "microplate" on which the northern part of Honshu rests (Figure 20-A). (Some geologists consider this part of Honshu to be on either the Eurasian Plate or the North American Plate.)

The severe ground shaking of the earthquake lasted for more than 3 minutes. During that time, a 300-kilometer-long by 150-kilometer-wide (185 mile by 90 mile) segment of the subduction zone slipped as much as 30 meters (100 feet). After the earthquake, the northeastern coast of Japan had jumped about 2.4 meters (8 feet) to the east, and parts of the coastline in Miyagi Prefecture had subsided by more than 1 meter (3.3 feet).



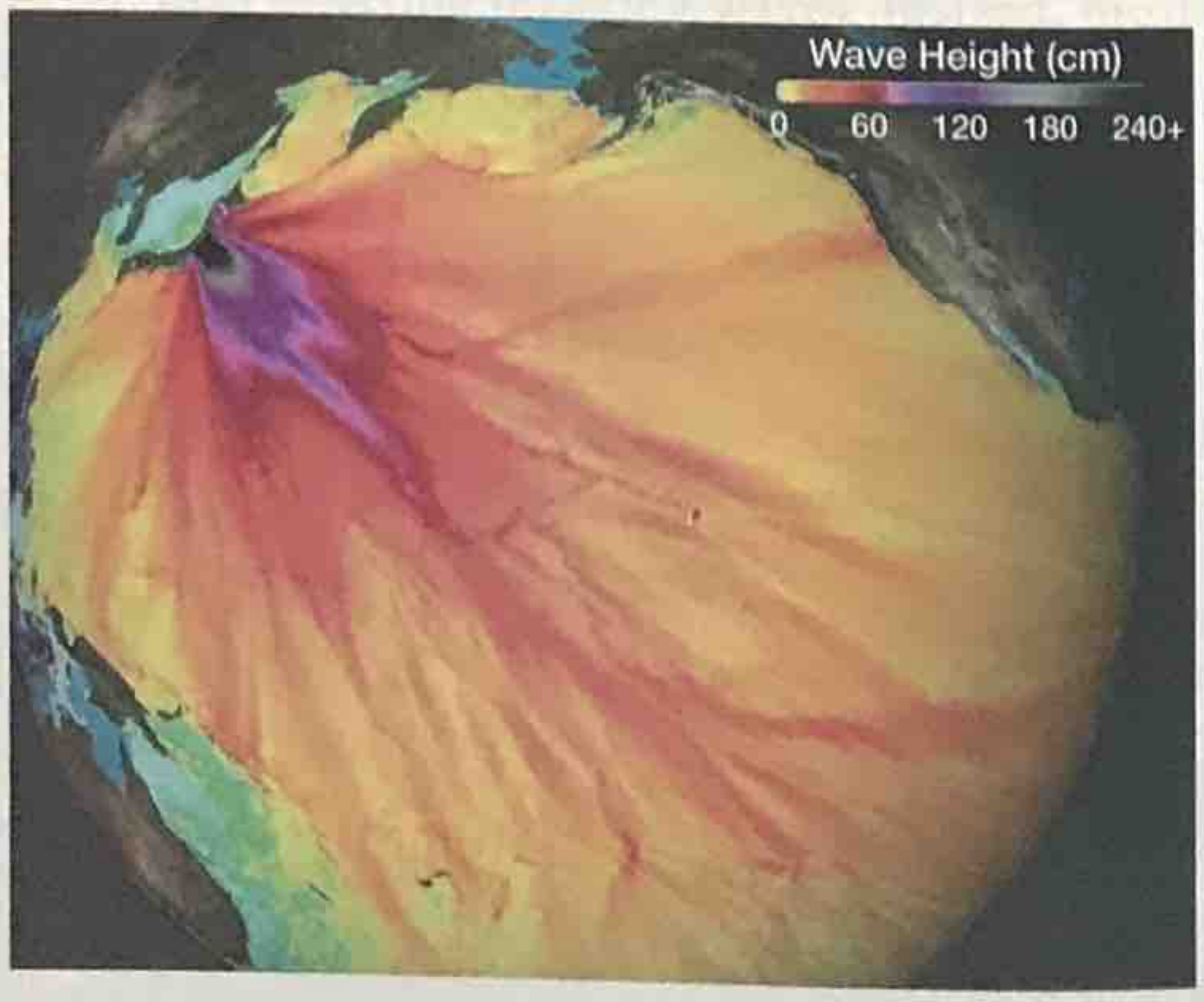
▲ **Figure 20-A** The 2011 Japan earthquake fault rupture zone. The maximum movement along the fault plane was more than 30 meters (100 feet), shown in red.

The Tsunami: Although the earthquake caused extensive damage, it was the tsunami that followed that was most deadly and destructive. The ocean floor above the fault rupture was abrupted uplifted, displacing an enormous volume of water. Tsunami warnings were issued in Japan within 10 minutes of the earthquake, but the coastal populations closest to the epicenter had almost no time to evacuate.

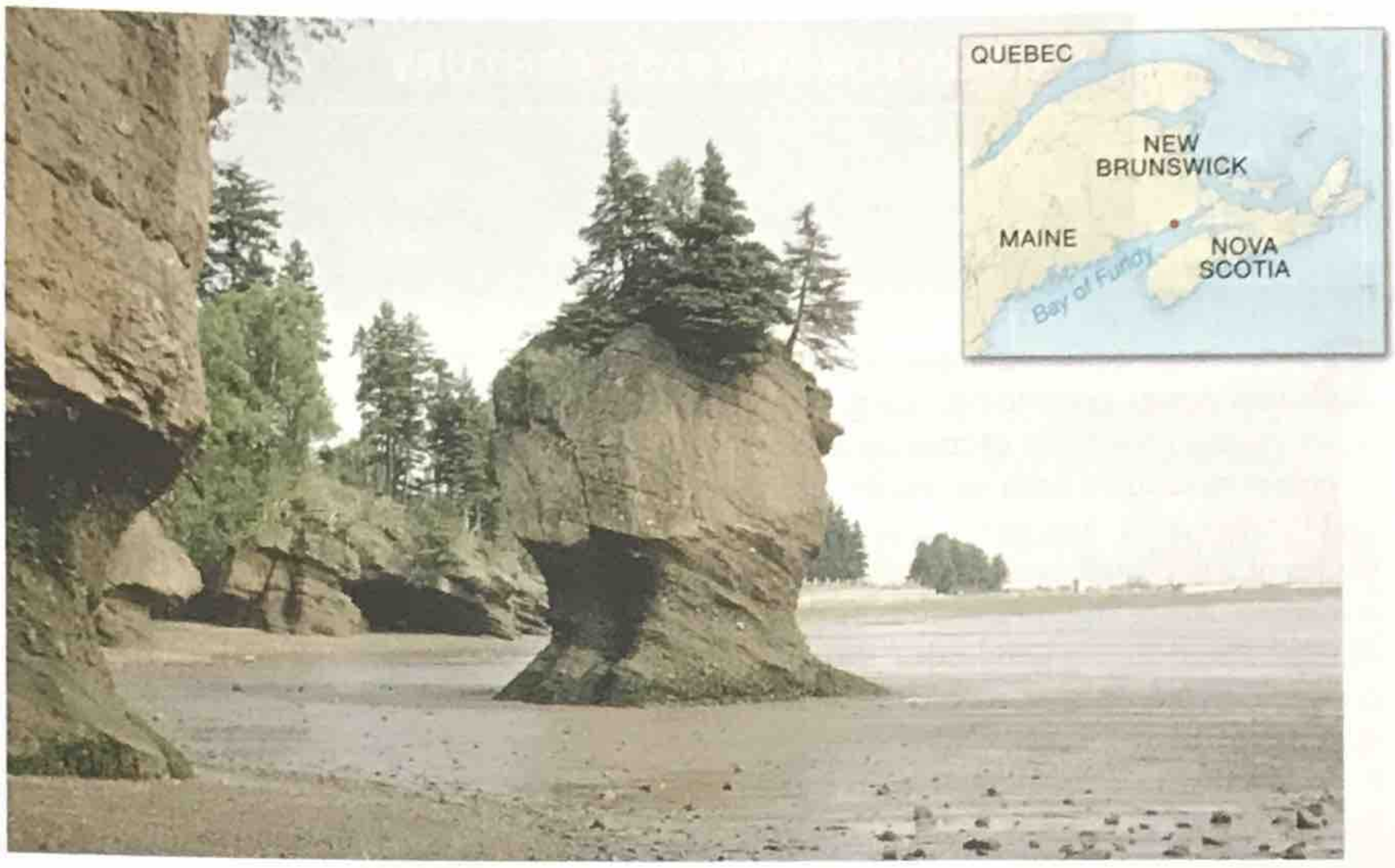
As the waves reached shallow water along the Japanese coast, wave height increased dramatically. The height of the tsunami along the coast was typically about 10 meters (33 feet), but in some confined harbors the height was more than 30 meters (100 feet). In low-lying coastal plains, such as in parts of the Sendai region north of Tokyo, the surge of water advanced as much as 10 kilometers (6 miles) inland, leveling buildings, ruining roads, and depositing tons of debris (Figure 20-B).

▲ **Figure 20-B** Tsunami coming onshore in Miyako, Iwate Prefecture, Japan on March 11, 2011.

Global Effects of the Tsunami: The tsunami was so large that it caused damage thousands of kilometers away. The tsunami waves spread out in all directions (Figure 20-C), racing across the Pacific Ocean at 800 kilometers per hour (500 mph). Small tsunami waves caused flooding in Hawai'i, and even damaged boats and harbors as far away as California—where one person was killed when he was swept offshore by the wave.



▲ **Figure 20-C** Map showing the estimated maximum height of the 2011 Japanese tsunami across the Pacific Ocean.



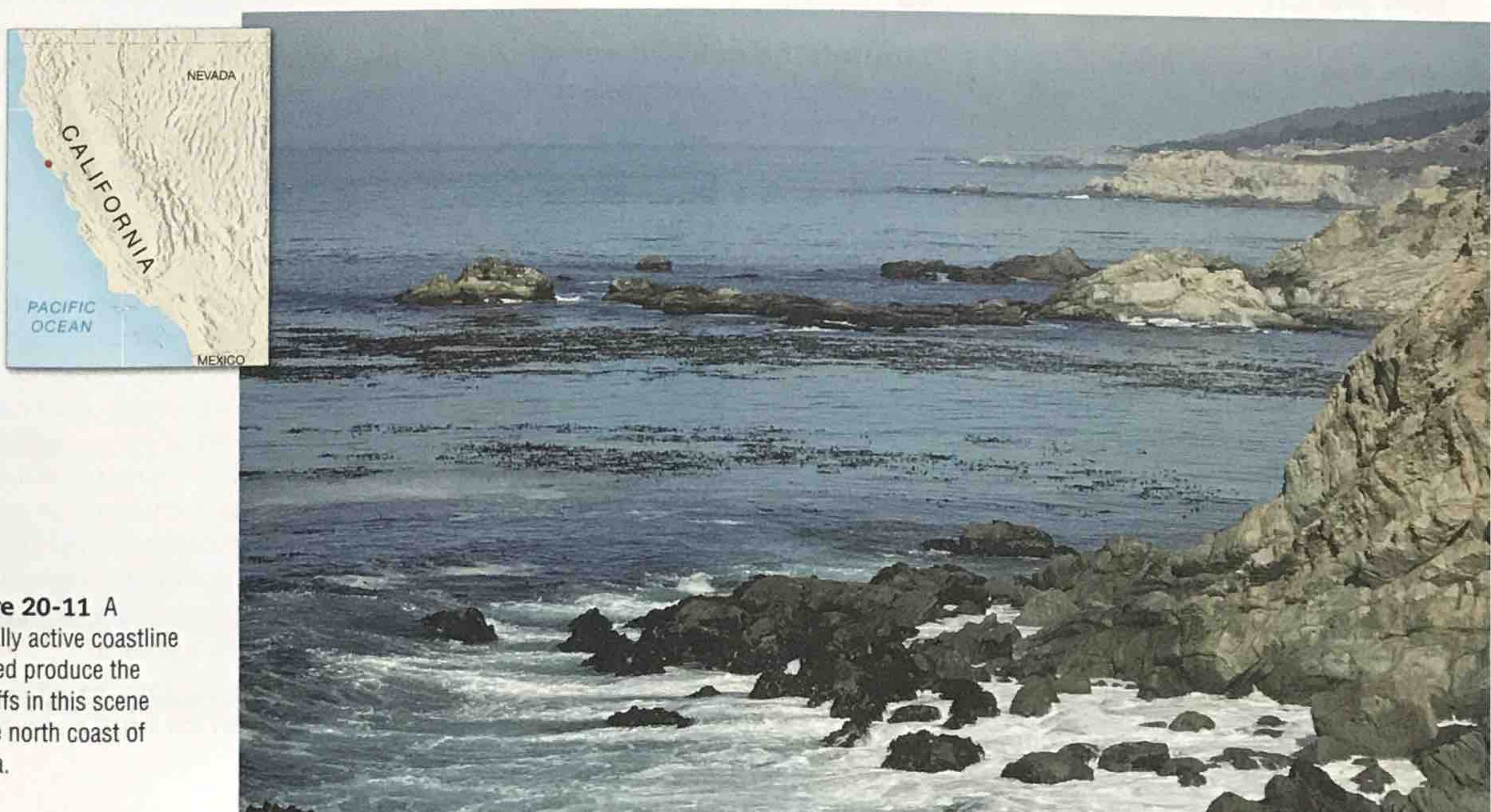
▶ **Figure 20-10** Under certain circumstances, a large tidal range can influence the shaping of coastal landforms. These gigantic pedestal rocks on the edge of the Bay of Fundy in New Brunswick, Canada, were carved by waves in this region which has the greatest tidal range in the world of up to 15 meters. For scale, the spruce trees on top of the rocks are about 9 meters (30 feet) tall.

sea-level change. During Earth's recent history, there have been many changes in sea level, sometimes worldwide and sometimes only around one or a few continents or islands. The eustatic changes of greatest magnitude and most extensive effect are those associated with seawater volume before, during, and after the Pleistocene glaciations. As we saw in Chapter 19, at the peak of the Pleistocene glaciations, sea level around the world was as much as 130 meters (430 feet) lower than today.

As a result of both tectonic and eustatic sea-level changes, many present-day ocean coastlines have been submerged, with a portion of a previous landscape now underwater, whereas others show emergent characteristics, in which shoreline topography of the past is now situated well above the contemporary sea level (Figure 20-11). We will consider the topographic consequences of these circumstances later in this chapter.

Most water-level changes in lakes are less extensive and less notable than those along ocean shorelines. These changes are usually the result of the total or partial drainage of a lake, and their principal topographic expression is exposed ancestral beach lines and wave-cut cliffs above present lake levels.

Global Warming and Sea-Level Change: In Chapters 4 and 8, we discussed the consequences of global climate change—especially what is commonly called "global warming." We noted that as global climate warms, there is a rise in sea level associated with the thermal expansion



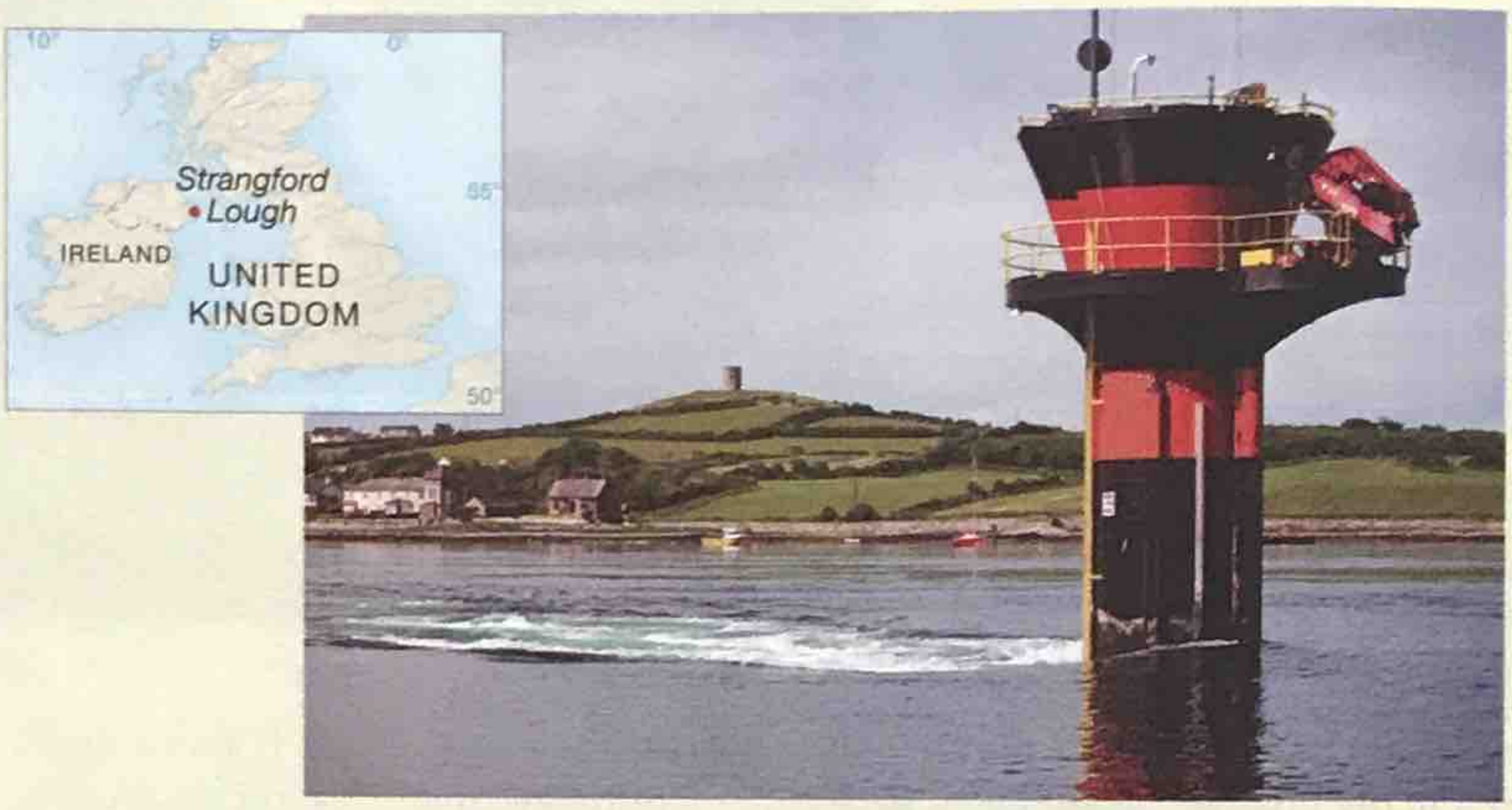
▶ **Figure 20-11** A tectonically active coastline has helped produce the sharp cliffs in this scene along the north coast of California.

ENERGY FOR THE 21ST CENTURY

Tidal Power

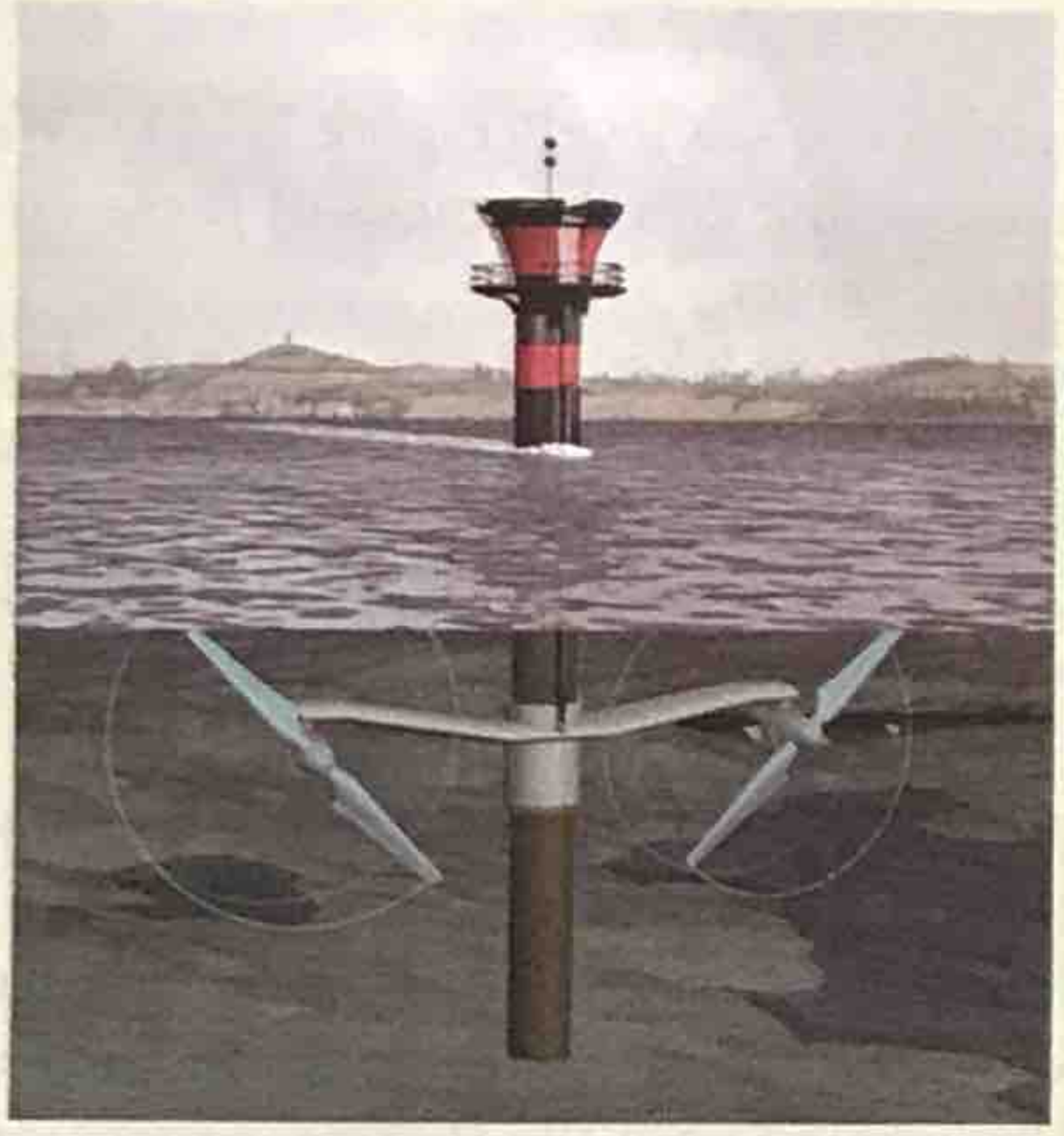
▶ Jennifer Rahn, Samford University, Birmingham, Alabama

Before large-scale commercial electrical power generation, many civilizations used the force of moving water to power machines such as textile mills and lumber mills. Just as wind turns the blades of a windmill, recent technological advances utilize the inflow and outflow of tidal water during flood tides and ebb tides to turn a turbine in order to generate electricity (Figure 20-D).



▲ **Figure 20-E** Tidal power turbine in Strangford Lough, Northern Ireland.

Tides are more predictable than solar power and wind energy—tides change twice a day (in some places just once a day) like clockwork—and the higher the tidal range, the greater the potential for tidal energy generation. The ideal locations for tidal power are areas with high flow volumes and/or high tidal ranges (see Figure 9-9).



▲ **Figure 20-D** Tidal power turbines generate electric power when tidal currents turn underwater propellers that in turn power generators.

Existing Tidal Power Installations: The first tidal power plant was built in 1966 in France, and the first one in North America was installed in the 1980s in an inlet of the Bay of Fundy in eastern Canada. One of the world's largest tidal power installations was completed in 2008 in Strangford Lough in Northern Ireland (Figure 20-E). The first commercial tidal power installation in the United States became operational in September 2012 off eastern Maine. Tidal power facilities have also been built in China, Russia, and South Korea.

Internationally, new tidal power projects have been proposed in the Philippines, India, New Zealand, and along the River Severn between Wales and England. In the United States, tidal power has been suggested for the Puget Sound in the Pacific Northwest, San Francisco Bay, New York's East River, Alaska, Hawai'i, and off Atlantic City, New Jersey.

Limitations of Tidal Power: Currently, tidal power is not widely used, in part because a limited number of places in the world have high-flow tidal regimes. Tidal-power projects are also extremely expensive because massive structures must be built in difficult saltwater environments. However, there are many long-term advantages for using this technology. Tidal power is a renewable energy resource with a virtually unlimited supply and no greenhouse gas emissions.

Estimates suggest that tidal power could meet 10 percent of the United States' and 20 percent of the United Kingdom's electricity demand within the next few decades. Globally, in about 10 years tidal energy could supply 10 percent of the world's energy if full commercialization of this technology materializes.

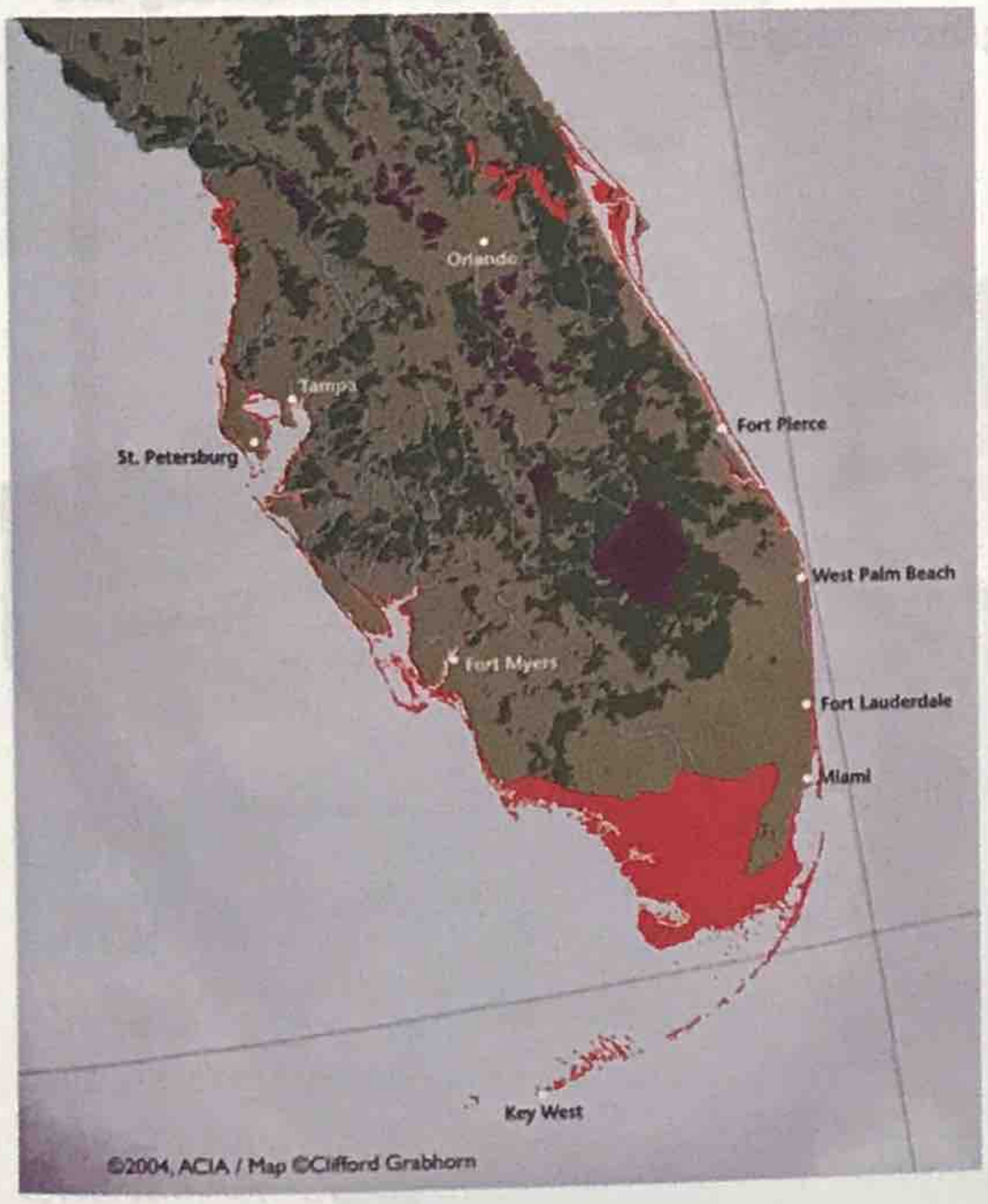
Technical Obstacles: The technology needed to efficiently and economically turn the tides into electricity is still being developed. Several new models for generating tidal power have been developed in recent years but none are operating commercially. Other problems include damage to the local aquatic environment, mostly with small fish getting caught in the rotors. Many people are hesitant to adopt large-scale tidal power plants because of the unknown harm they could cause the environment. As we are now seeing with dammed rivers, when humans alter the flow of energy and the surrounding environment, many times there are unintended consequences.

The growth of tidal power generation will depend on the public and political desire for governments to make the large investment needed for this type of alternative energy. Also important are the efforts of green energy entrepreneurs to develop better and more cost-effective infrastructure, as well as the ability of scientists to predict the major environmental effects of individual projects ahead of time in order to protect local ecosystems.

of ocean water as well as the increase in volume from the melting of continental glaciers and ice caps. If worldwide temperature continues to warm, we can anticipate an ongoing period of deglaciation, with the ice sheets of Antarctica and Greenland slowly melting. Such a situation would cause a global eustatic rise in sea level that would inundate many islands and coastal plains of the world, and would expose coastal populations to greater risks from storm waves such as those generated by hurricanes.

Should the ice caps of Antarctica and Greenland melt completely (a result not anticipated by most climate scientists, even over the next century or so), global sea level would rise by about 80 meters (260 feet). However, even a modest increase in global sea level will be potentially devastating to populations now living in low-lying coastal areas. Given the anticipated levels of greenhouse gases and the associated temperature rise due to global warming, in 2007 the *Fourth Assessment Report* of the Intergovernmental Panel on Climate Change projected a sea level rise of 0.18 to 0.59 meters (7.1 to 23.2 inches) by the end of this century. More recent studies suggest that the rise could be as much as 1.4 meters (55 inches), with some projections suggesting even more. Such an increase in sea level would cause shorelines around the world to retreat on average more than 30 meters (about 100 feet)—eliminating thousands of square kilometers of coastal land in North America alone. With such an increase in global sea level, some island countries would literally disappear (Figure 20-12).

Learning Check 20-5 **Explain how current climate change may affect the coastlines of oceans.**



▲ **Figure 20-12** NASA map with red showing the estimated coastal area of southern Florida that will be flooded by a 1-meter rise in sea level.

Ice Push

The shores of bodies of water that freeze over in winter are sometimes significantly affected by *ice push*, which is usually the result of the contraction and expansion that occurs when the water freezes and thaws as the weather changes. As more and more water turns to ice—and therefore expands in volume (recall the discussion of *frost wedging* in Chapter 15)—near-shore ice is shoved onto the land, where it can deform the shoreline by pushing against it, more or less in the fashion of a small glacial advance.

Ice push is usually unimportant on seashores outside the Arctic and Antarctic, but it can be responsible for numerous minor alterations of the shorelines of high-latitude or high-elevation lakes.

Organic Secretions

Several aquatic animals and plants produce solid masses of rocklike material by secreting calcium carbonate. By far the most significant of these organisms is the coral *polyp*, a tiny animal that builds a hard external skeleton of calcium carbonate and then lives inside it. Coral polyps are of many species, and they cluster together in social colonies of uncounted billions of individuals. Under favorable conditions (clear, shallow, salty warm water), the coral can accumulate into enormous masses, forming reefs, platforms, and atolls, all commonplace features in tropical and subtropical oceans. (Coral reef structures will be discussed later in this chapter.)

Stream Outflow

The source of most sediment deposited in shoreline beaches and other depositional features is the outflow from streams, although in some locations all or part of the sediment may come directly from the erosion of coastal rocks. As we saw in Chapter 16, in some cases the sediment carried by streams is deposited as alluvium in a delta. Even in such cases, at least some of the sediment carried by streams into the ocean is further transported and then deposited elsewhere by coastal waters (Figure 20-13).

Learning Check 20-6 **What is the source of most coastal sediment?**

Coastal Sediment Transport

FG8

Animation
Coastal Sediment Transport

Many kinds of currents flow in the oceans and lakes of the world, but nearly all transportation of sediment along coastlines is accomplished by wave action and local currents.

Longshore Currents: Coastal topography is affected most by **longshore currents**, in which the water and sediment move roughly parallel to the shoreline. (Think of *longshore* as a contraction for "along the shore.") Longshore currents develop just offshore and are set up by the action of the waves striking the coast at a

▲ **Figure 20-13** The sediment plume of the Fraser River where it enters the ocean at Vancouver, Canada.

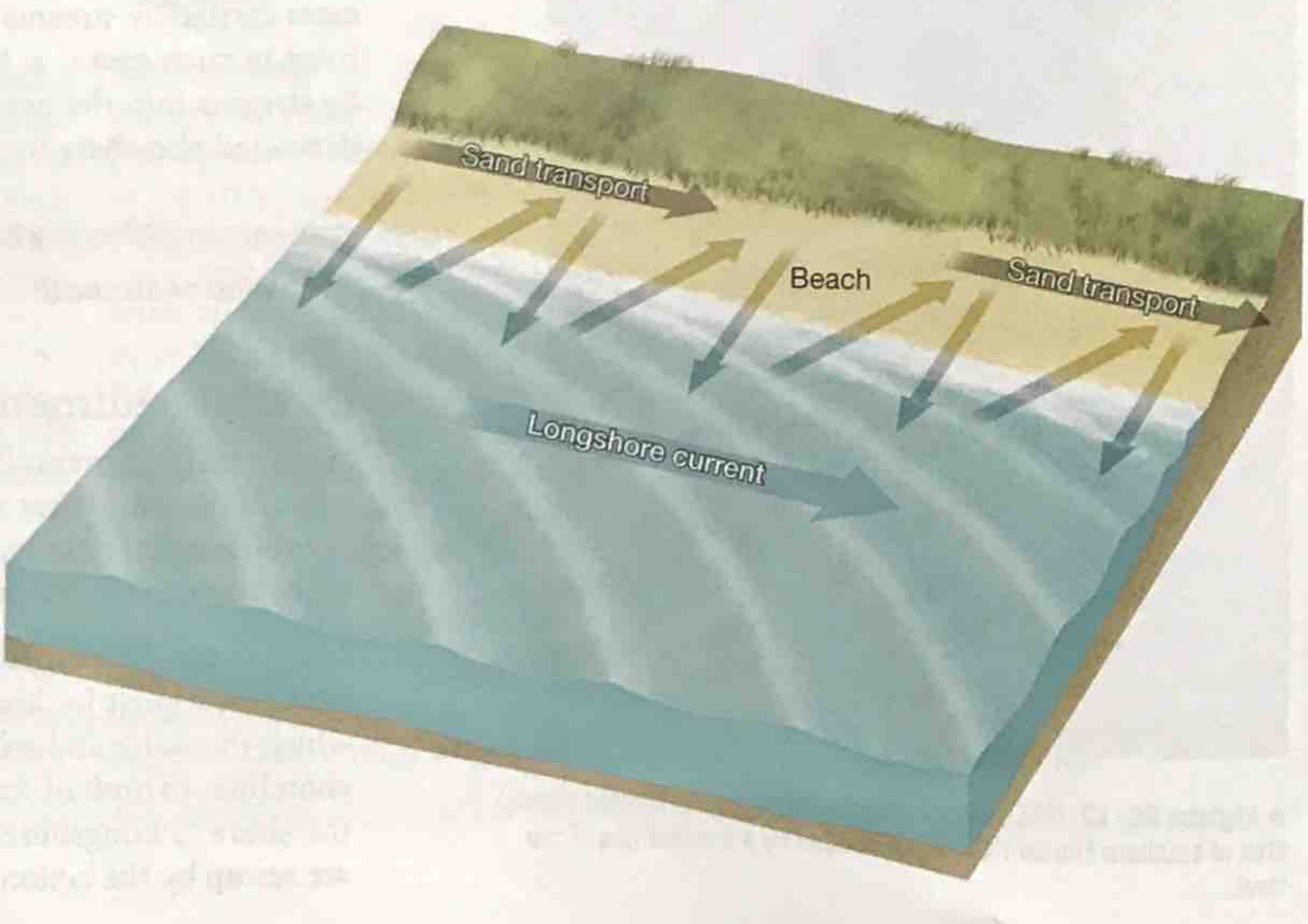
slight angle (Figure 20-14). Because most waves are generated by wind, the direction of a longshore current typically reflects the local wind direction. Longshore currents are prominent transporters of sand and other sediment along many shorelines.

Beach Drifting: Another significant mechanism of coastal sediment transport involves the short-distance shifting of sand directly onshore by breaking waves and the retreating water from the beach. This movement takes the form of **beach drifting** along a coastline, a zigzag movement of sediment that results in a general downwind displacement parallel to the coast (see Figure 20-14). Nearly all waves approach the coast obliquely rather than at a right angle (Figure 20-15), and therefore the sand and other debris carried onshore by the breaking wave move up the beach at an oblique angle. Some of the water soaks into the beach, but much of it returns seaward directly downslope, which is normally at a right angle to the shoreline. This return flow takes some of the sand with it, much of which is picked up by the next surging wave and carried shoreward again along an oblique path. This infinitely repetitious pattern of movement shifts the debris farther and farther along the coastline. Because wind is the driving force for wave motion, the strength, direction, and duration of the wind are the principal determinants of beach drifting.

Video
Movement of Sand in Beach Compartment

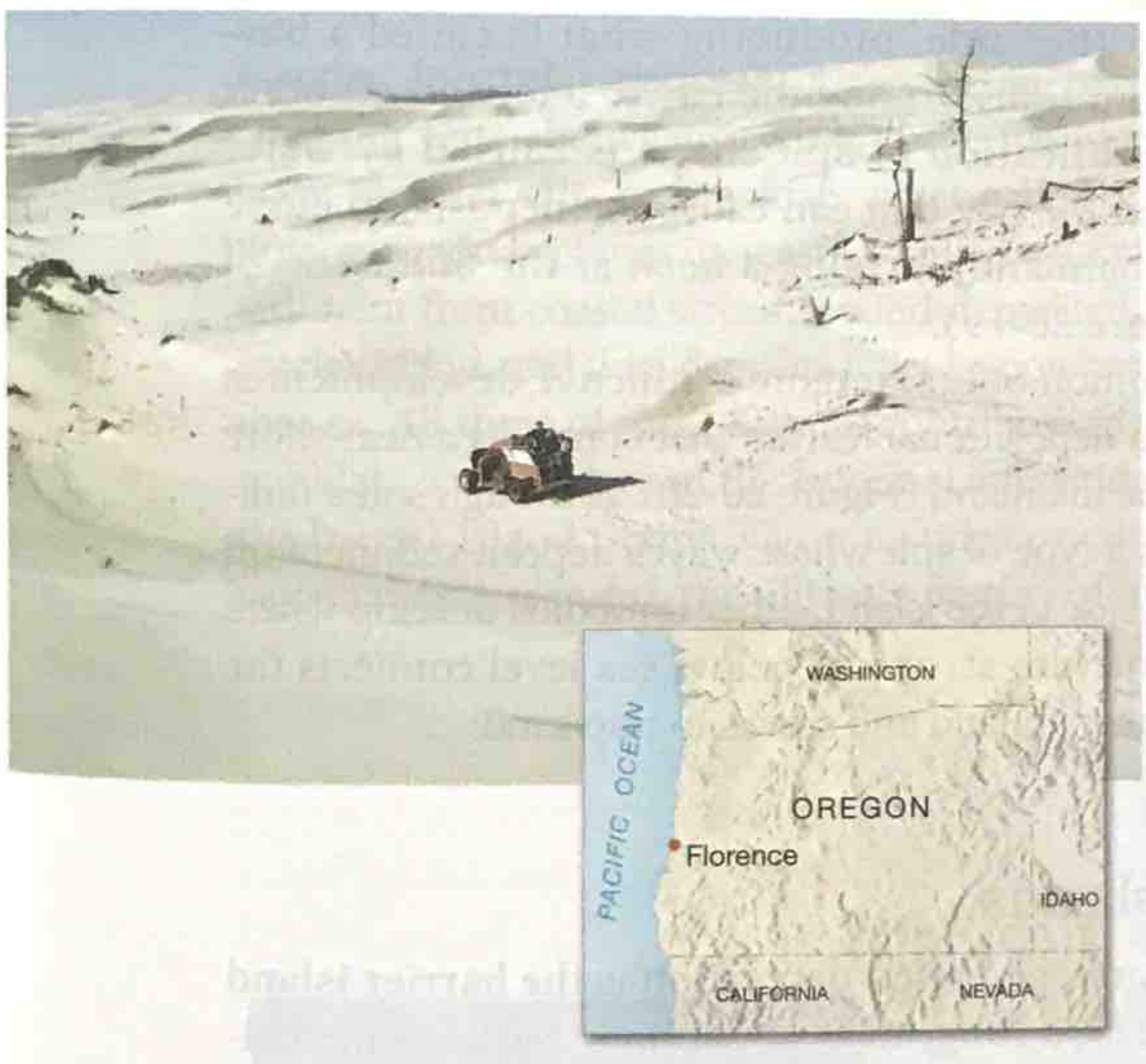
Some sediment transport along shorelines is accomplished directly by the wind. Wherever waves have carried or hurled sand and finer-grained particles to positions above the water level, these particles can be picked up by a breeze and moved overland. This type of movement frequently results in dune formation and sometimes moves sand a considerable distance inland (Figure 20-16; see Chapter 18 for a more lengthy discussion of sand dunes).

Learning Check 20-7 **Explain the coastal sediment transport processes of beach drifting and longshore currents.**



▶ **Figure 20-14** Beach drifting involves a zigzag movement of sand along the coast. Sand is brought obliquely onto the beach by the wave and is then returned seaward by the backwash. Longshore currents develop just offshore and move sediment parallel to the coastline. Because most waves develop in response to the wind, longshore currents and beach drifting typically move sediment in a general downwind direction along a shore.

▲ **Figure 20-15** Here, a series of wave roll in obliquely to the beach at Cape Byron, on the eastern coast of Australia. The direction of beach drifting would be from the bottom of the photograph toward the top.



▲ **Figure 20-16** Sand is sometimes heaped into dunes that cover extensive areas. One of the largest sand accumulations in North America is along the central coast of Oregon, near Florence.

COASTAL DEPOSITIONAL LANDFORMS

FG2, FG8

Although the restless waters of coastal areas accomplish notable erosion and transportation, in many cases the most conspicuous topographic features of a shoreline are formed by the deposition of sediment, especially sand-size sediment. Just as with streamflow on the surface of a continent, coastal deposition occurs wherever the energy of moving water is diminished.

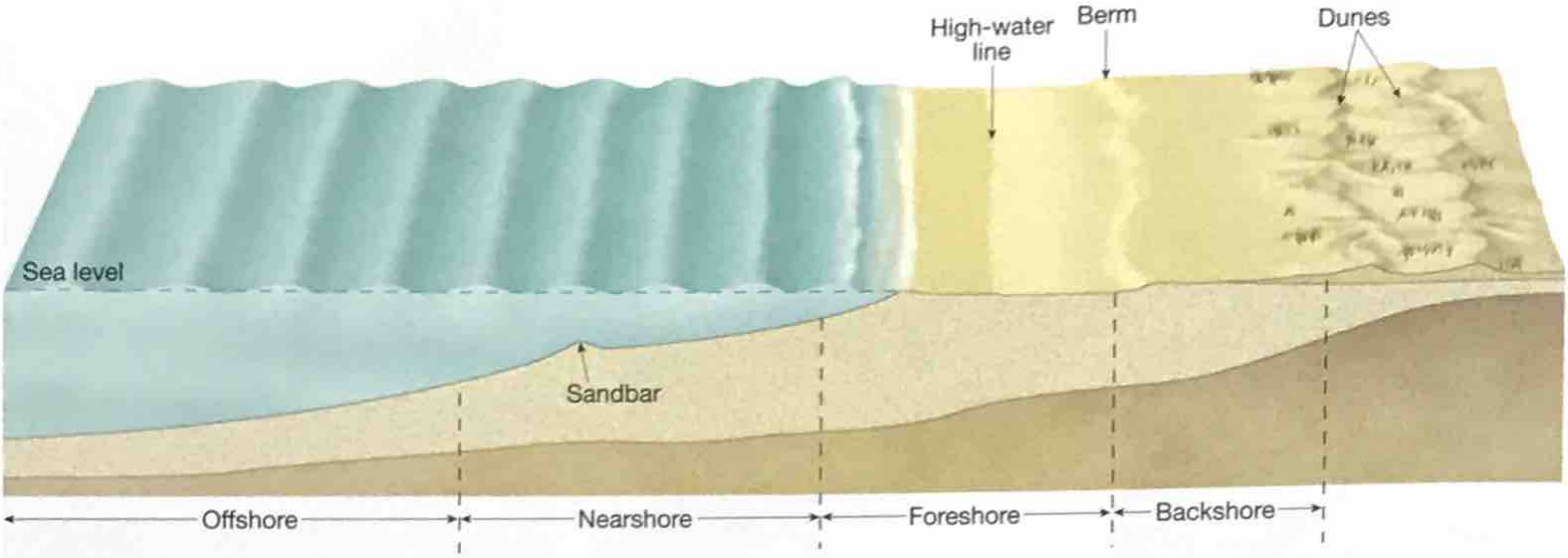
Sediment Budget of Depositional Landforms

Maritime deposits along coastlines tend to be more ephemeral than noncoastal deposits. This is due primarily to the composition of marine deposits, which typically consist of relatively small particles (sand and gravel), and to the fact that the sand is not stabilized by a vegetation cover. Most coastal deposits are under constant onslaught by agitated waters that can rapidly wash away portions of the sediment. Consequently, the **sediment budget** must be in balance if the deposit is to persist; for the budget to be in balance, removal of sand must be offset by addition of sand. Most marine deposits have a continuing sediment flux, with debris arriving in some places and departing in others. During storms, the balance is often upset, with the result that the deposit is either significantly reshaped or totally removed, only to be replaced when calmer conditions prevail.

Beaches

The most widespread marine depositional feature is the **beach**, which is an exposed deposit of loose sediment adjacent to a body of water. Although the sediment can range in size from fine sand to large cobbles, it is usually relatively homogeneous in size on a given section of beach. Beaches composed of smaller particles (which is to say sand, because silt and clay get carried away in suspension and do not form beaches) are normally broad and slope gently seaward, whereas those formed of larger particles (gravel, cobbles) generally slope more steeply.

Beach Profiles: Beaches occupy the transition zone between land and water, sometimes extending well above the normal sea level into elevations reached only by the highest storm



▲ **Figure 20-17** An idealized beach profile.

waves. On the seaward side, they generally extend down to the level of the lowest tides and can often be found at still lower levels, where they merge with muddy bottom deposits. Figure 20-17 portrays an idealized beach profile.

The *backshore* is the upper part of the beach, landward of the high-water line. It is usually dry, being covered by waves only during severe storms. It contains one or more *berms*, which are flattish wave-deposited sediment platforms. The *foreshore* is the zone that is regularly covered and uncovered by the rise and fall of tides. The *nearshore* extends from the low-tide mark, seaward to where the low-tide breakers begin to form—the nearshore is not exposed to the atmosphere, but it is the place where waves break and where surf action is greatest. The *offshore* zone is permanently underwater and deep enough that wave action rarely influences the bottom.

Beaches sometime extend for dozens of kilometers along straight coastlines, particularly if the relief of the land is slight and the bedrock unresistant. Along irregular shorelines, beach development may be restricted largely or entirely to bays, with the bays frequently alternating with rocky headlands.

Beach shape may change greatly from day to day and even from hour to hour—anytime the sediment budget of the beach changes. Normally beaches are built up during quiet weather and removed rapidly during storms. Most midlatitude beaches are longer and wider in summer and greatly worn away by the storminess of winter.

Video
Summertime/
Wintertime
Beach
Conditions

Learning Check 20-8 **What is the *sediment budget* of a beach, and how can it change?**

Spits

At the mouth of a bay, sediment transported by longshore currents moves into deeper water. There the flow speed is slowed and the sediment is deposited. The growing bank of land guides the current farther into the deep water, where still more material is dropped. Any such linear deposit attached to the land at one end and extending into open water in a downcurrent direction is called a **spit** (Figure 20-18).

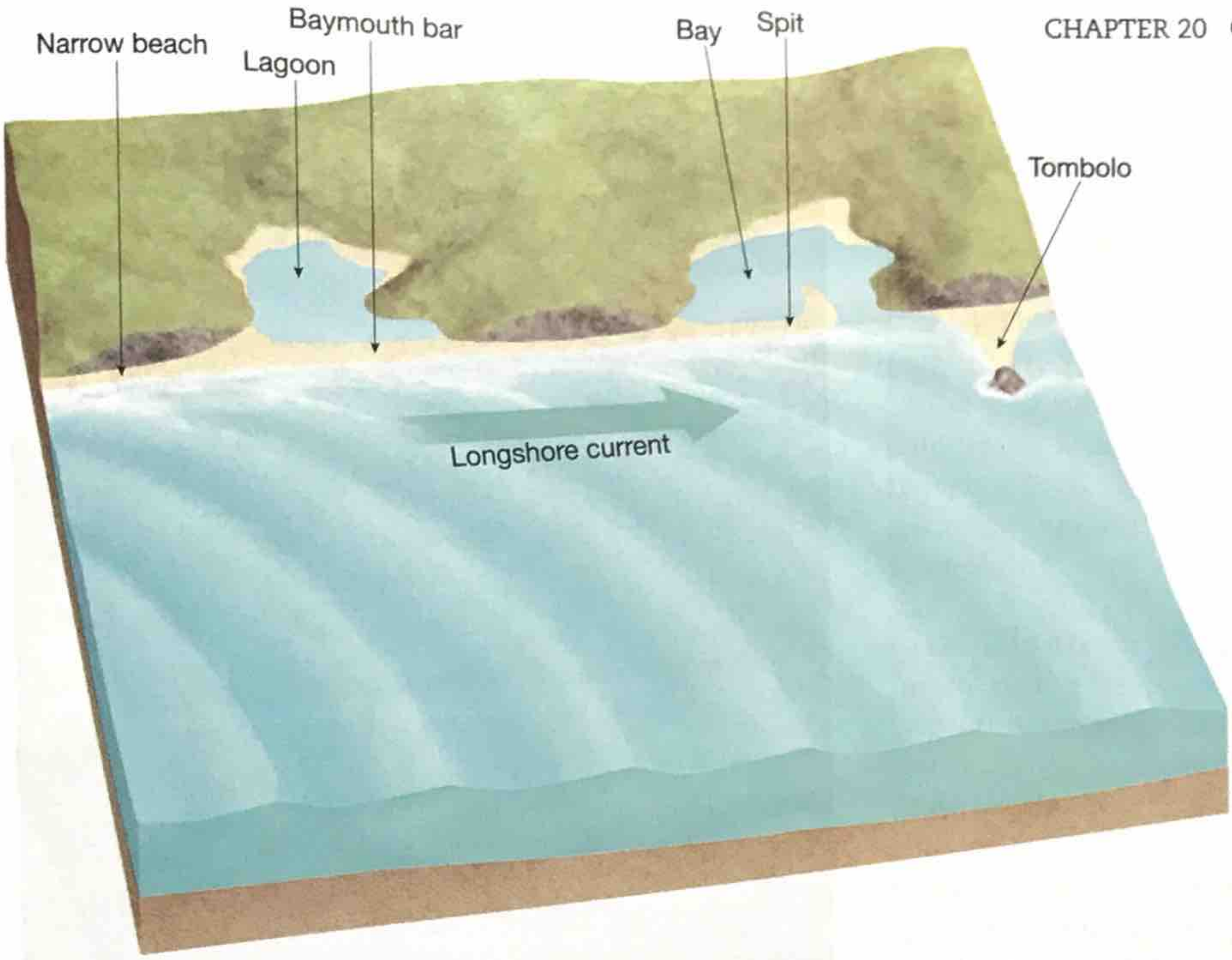
Although most spits are straight, sandy peninsulas projecting out into a bay or other coastal indentation, variations in local currents, winds, and waves often give them other configurations. In some cases, the spit becomes extended clear across the mouth of a bay to connect with land on the other side, producing what is called a **baymouth bar** and transforming the bay to a lagoon. Another common modification of spit shape is caused by water movements in the bay that can cause the deposits to curve toward the mainland, forming a *hook* at the outer end of the spit (Figure 20-19).

A less common but even more distinctive development is a **tombolo**—a depositional feature that connects a near-shore island with the mainland (Figure 20-20). Although some tombolos form as a type of spit where waves deposit sediment on the landward side of the island, other tombolos develop where a bedrock structure at, or just below, sea level connects the island with the mainland and serves to trap sand.

Barrier Islands

Another prominent coastal deposition is the **barrier island** (Figure 20-21), a long, narrow sandbar built up in shallow offshore waters, sometimes only a few hundred meters from the coast but often several kilometers at sea. Barrier islands are always oriented approximately parallel to the shore. They are believed to result from the deposition of sediment where large waves (particularly storm waves) begin to break in the shallow waters of continental shelves. However, many larger barrier islands may have more complicated histories linked to the lowered sea level during the Pleistocene.

Barrier islands often become the dominant element of a coastal terrain. Although they usually rise at most only a few meters above sea level and are typically only a few hundred meters wide, they may extend many kilometers in length. Most of the Atlantic and Gulf of Mexico coastline of the United States, for instance, is paralleled by lengthy



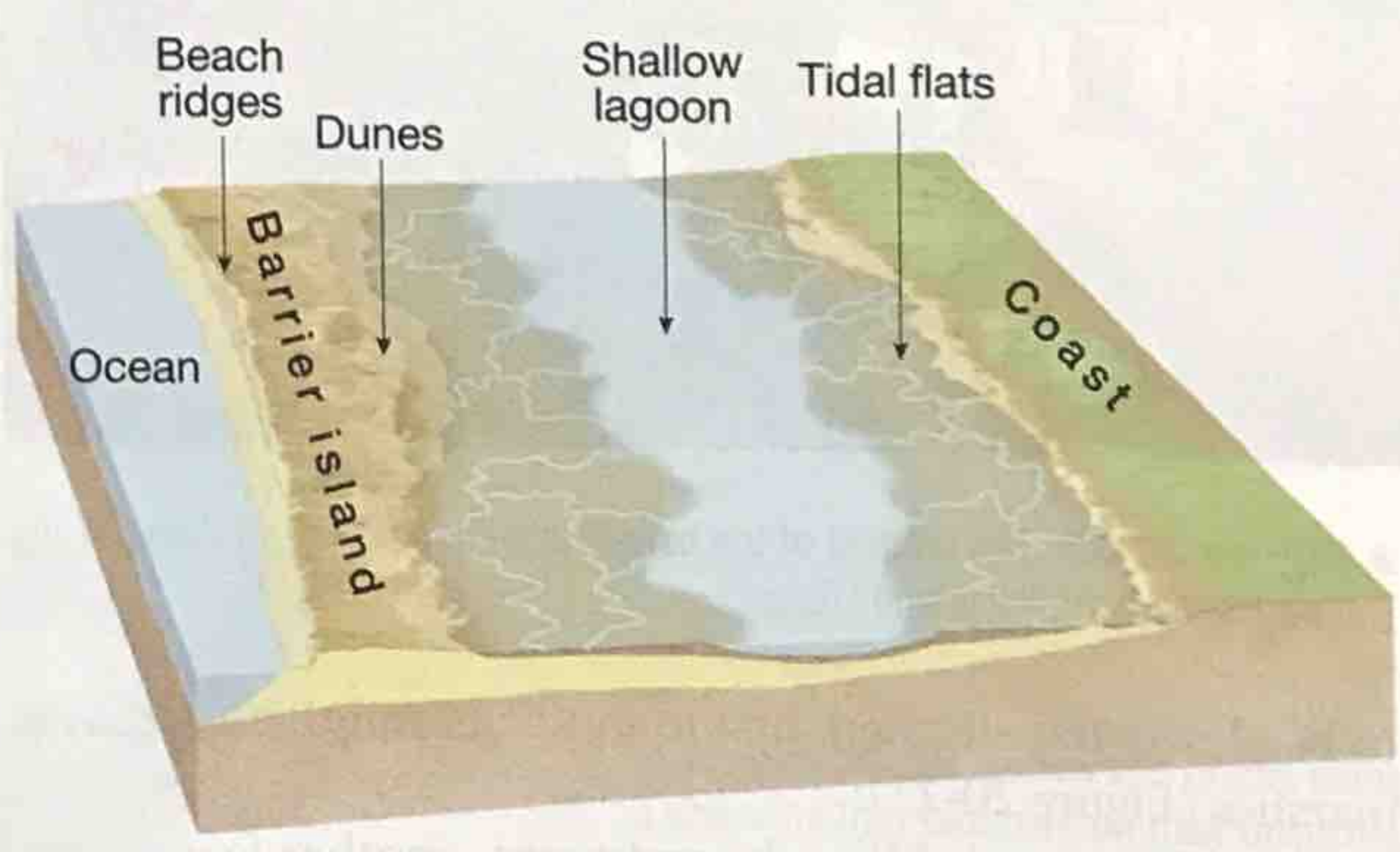
◀ **Figure 20-18** Common depositional landforms along a coastline include spits, baymouth bars, and tombolos. Note the orientation of the spit to the direction of the longshore current.

barrier islands, several more than 50 kilometers (30 miles) long (Figure 20-22).

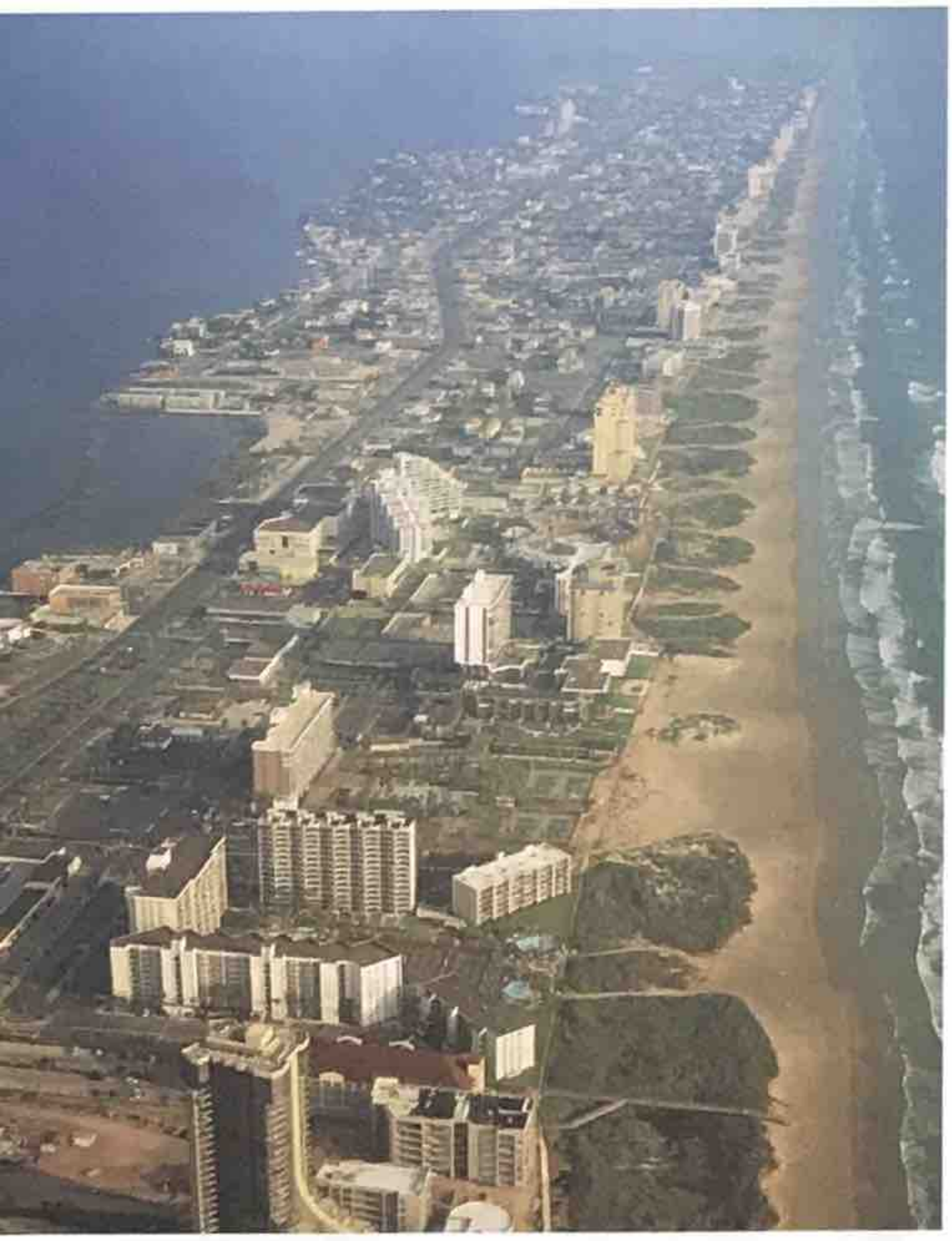
Barrier Island Lagoons: An extensive barrier island isolates the water between itself and the mainland, forming a body of quiet salt- or brackish water called a **lagoon**. Over time, a lagoon becomes increasingly filled with water-deposited sediment from coastal streams, wind-deposited sand from the barrier island, and tidal deposits if the lagoon has an opening to the sea. All three of these sources contribute to the buildup of mudflats on the edges of the lagoon. Unless tidal inlets across the barrier island permit vigorous tides or currents to carry lagoon debris seaward, the ultimate destiny of most lagoons is

▲ **Figure 20-20** This tombolo connects the nearshore island of Point Stephens to the mainland in Tomaree National Park, New South Wales, Australia.

▲ **Figure 20-19** Farewell spit on the South Island of New Zealand has developed a slight hook that curves back toward shore.



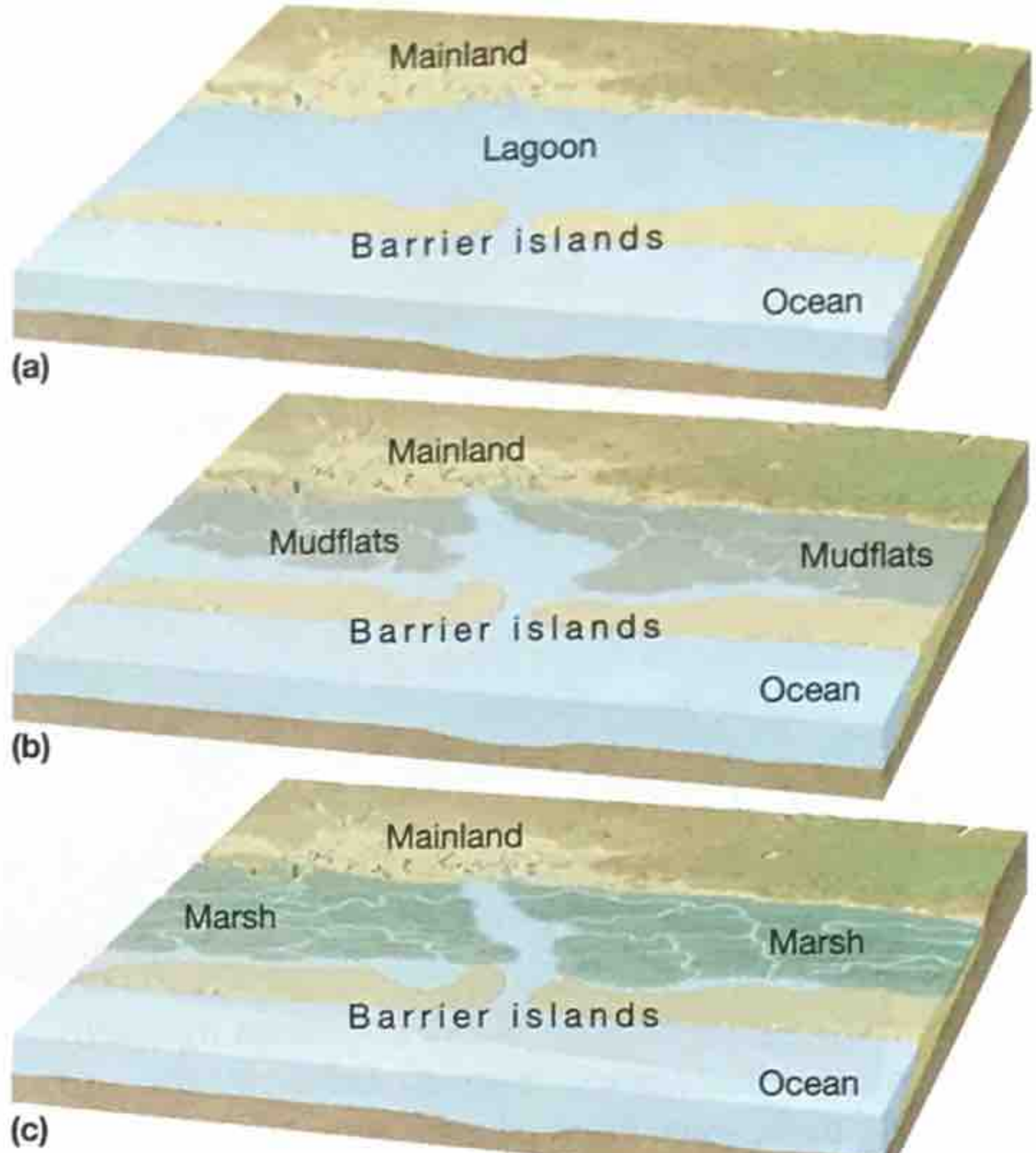
▲ **Figure 20-21** A typical relationship between ocean, barrier island, and lagoon.



▲ **Figure 20-22** The longest of the barrier islands off the Gulf Coast of the United States is Padre Island, Texas.

to be slowly transformed, first to mudflats and then to coastal marshes (Figure 20-23).

In addition to infilling by sediment, another factor contributes to a lagoon's disappearance. After a barrier island



▲ **Figure 20-23** Barrier islands are separated from the mainland by lagoons (a). With the passage of time, the lagoons often become choked with sediment and become converted to mudflats (b) or marshes (c).

becomes a certain size, it often begins to migrate slowly shoreward as waves wear away its seaward shore and sediments accumulate to build up its landward shore. Eventually, if the pattern is not interrupted by such things as changing sea level, the island and the mainland shore will merge.

Animation
Movement of Barrier Island

Because most barrier islands rise just a few meters above sea level and are largely built up of coastal sediment, they can be quite susceptible to damage from large storms. A number of inhabited barrier islands along the Gulf Coast of the United States experienced severe erosion during hurricanes such as Lili in 2002, Katrina in 2005 (Figure 20-24), Ike in 2008, and Sandy in 2012. With even the slight rise in global sea level anticipated this century by the Intergovernmental Panel on Climate Change, barrier islands will become even more vulnerable to storm waves.

Human Alteration of Coastal Sediment Budgets

Over the last century, human activity has disrupted the sediment budgets of beaches along many shorelines of the world—this has been especially true in many coastal areas of North America. For example, dams built along rivers for flood control or hydroelectric power generation effectively act as sediment traps. With less sediment reaching the mouths of rivers, there

Animation
Coastal Stabilization Structures

▲ **Figure 20-24** Dauphin Island south of Mobile, Alabama, experienced extensive erosion from storm waves during Hurricane Katrina in 2005. The top photograph was taken on July 21, 2001, before Katrina. The bottom photograph was taken on August 31, 2005, after the passage of Hurricane Katrina. The oil rig in the foreground was washed onto the island during the storm.

is less sediment to be transported along the shoreline by longshore currents and beach drifting, and so the downcurrent beaches begin to shrink. In addition, artificial structures built by one community to increase or stabilize their beaches may reduce the amount of sediment transported farther down a shoreline, thus causing downcurrent beaches to be reduced in size.

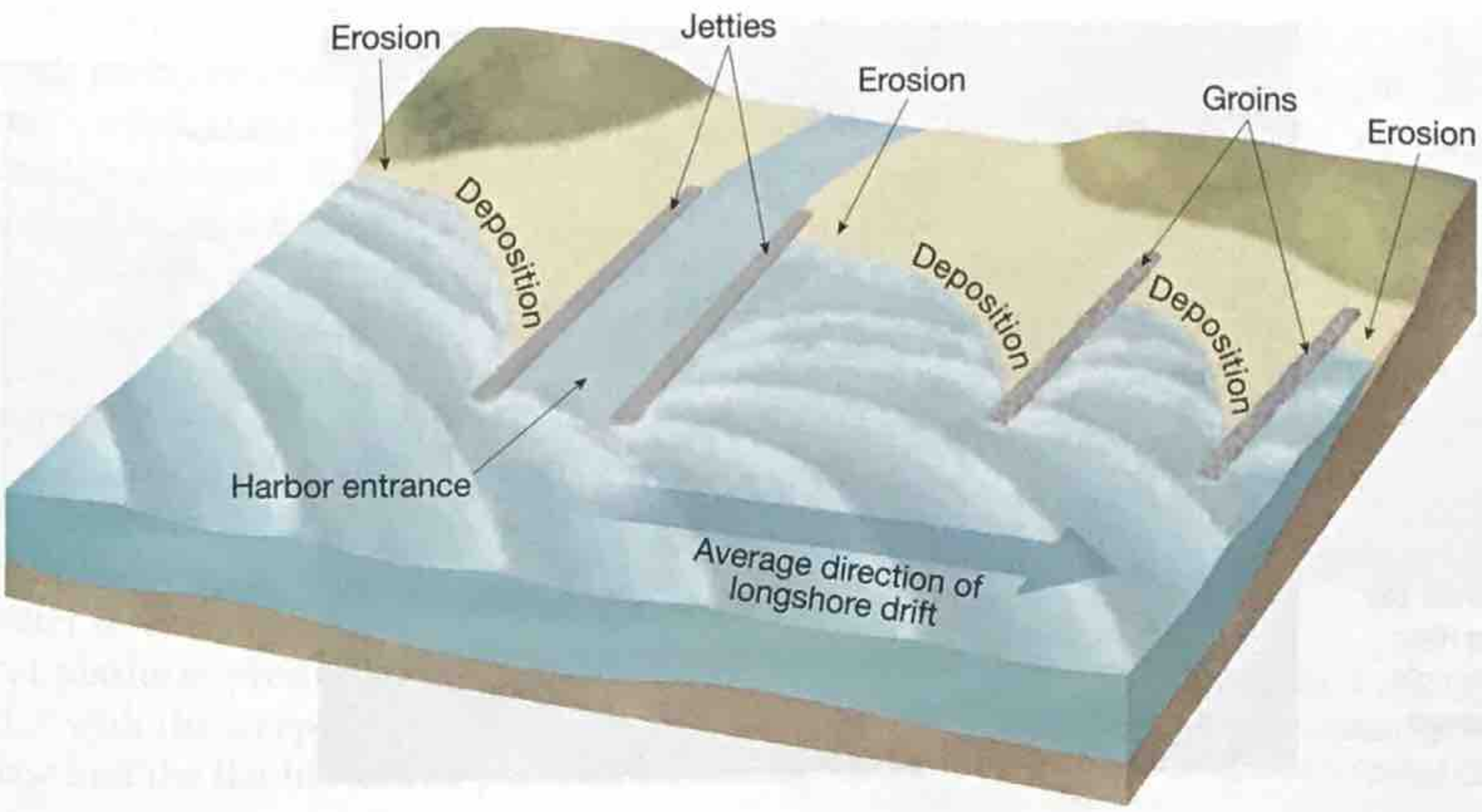
Beach Nourishment: Local communities have taken a number of different approaches to solving the problem of shrinking beaches. One direct, but relatively expensive, approach is to "nourish" a beach by dumping tons of sand just slightly upcurrent of the beach. Unfortunately, since longshore currents and beach drifting will eventually transport the sand away, such nourishment must be undertaken repeatedly in order to maintain the beach at a desired size. Many of the most famous beaches in the world are maintained through such nourishment, including Hawai'i's iconic Waikīkī Beach in Honolulu.

Stabilization Structures: Another approach to maintaining beaches is the use of "hard" stabilization structures. For example, a **groin** is a short wall or dam built out from a beach to impede the longshore current and force sand deposition on the upcurrent side of the structure (Figure 20-25). Although groins do trap sediment on their upcurrent side, erosion tends to take place on their downcurrent side; to reduce this erosion, another groin can be built just downcurrent. In some locations, a series of groins, known as a *groin field*, has been built (Figure 20-26).

Jetties are usually built in pairs on either side of a river or harbor entrance. The idea is to confine the flow of water to a narrow zone, thereby keeping the sand in motion and inhibiting its deposition in the navigation channel. Jetties tend to interfere with longshore currents in the same way as groins, trapping sand on the upcurrent side while causing erosion on the downcurrent side.

Even after undertaking such expensive projects as building groin fields and carrying out regular beach nourishment, some communities are finding that it is a losing proposition—the beaches continue to shrink and there seems to be no clear solution available to them.

Learning Check 20-9 **How do groins and jetties typically influence the beach around them?**



◀ **Figure 20-25** Jetties and groins along a shoreline trap sediment on their upcurrent side, while erosion tends to remove sediment on their downcurrent side.

▲ **Figure 20-26** Groin field along Norderney Island in northern Germany. The dominant direction of the longshore current is from left to right.

SHORELINES OF SUBMERGENCE AND EMERGENCE

One of the most conspicuous changes influencing coastal topography, especially oceanic coastlines, comes from a change in the relative height of the water relative to the coastal land—a relative rise in sea level leading to a *shoreline of submergence*, or a relative rise in the land leading to a *shoreline of emergence*. As we've seen, such changes can occur from either an actual increase or decrease in the amount of ocean water, or when the land is tectonically rising or sinking relative to the ocean.

Coastal Submergence

In the recent geological past, sea level has fluctuated sharply. For example, during a warmer climatic interval in an interglacial period, 125,000 years ago, sea level was about 6 meters (20 feet) higher than it is today. During the last glacial peak (about 20,000 years ago), sea level is estimated to have been about 120 meters (400 feet) lower than it is at present.

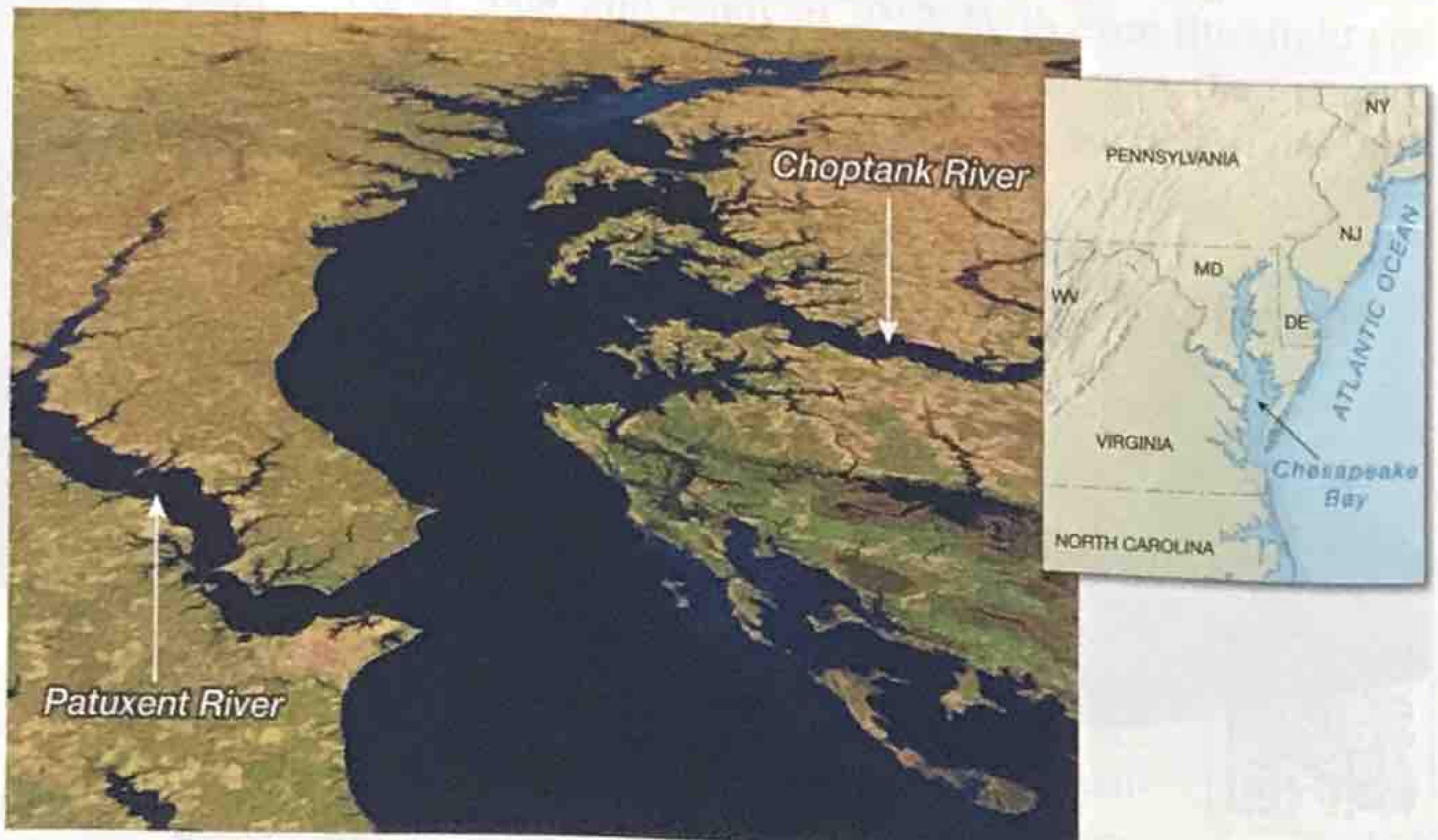
Almost all the world's oceanic coastlines show evidence of submergence during the last 15,000 years or so, a result of the melting of the Pleistocene ice sheets. As water from melting glaciers returned to the oceans, rising sea level caused widespread submergence of coastal zones. Further, as contemporary global warming leads to a slight increase in sea level, a slow but gradual expansion of flooded shorelines is expected to continue during this century.

Ria Shorelines: The most prominent result of submergence is the drowning of previous river valleys, which produces *estuaries*, or long fingers of seawater projecting inland. A coast along which there are numerous estuaries is called a **ria shoreline**. A ria (from the Spanish *ría*, meaning "river") is a long, narrow inlet of a river that gradually decreases in depth from mouth to head (Figure 20-27). If a hilly or mountainous coastal area is submerged, numerous offshore islands may indicate the previous location of hilltops and ridge crests.

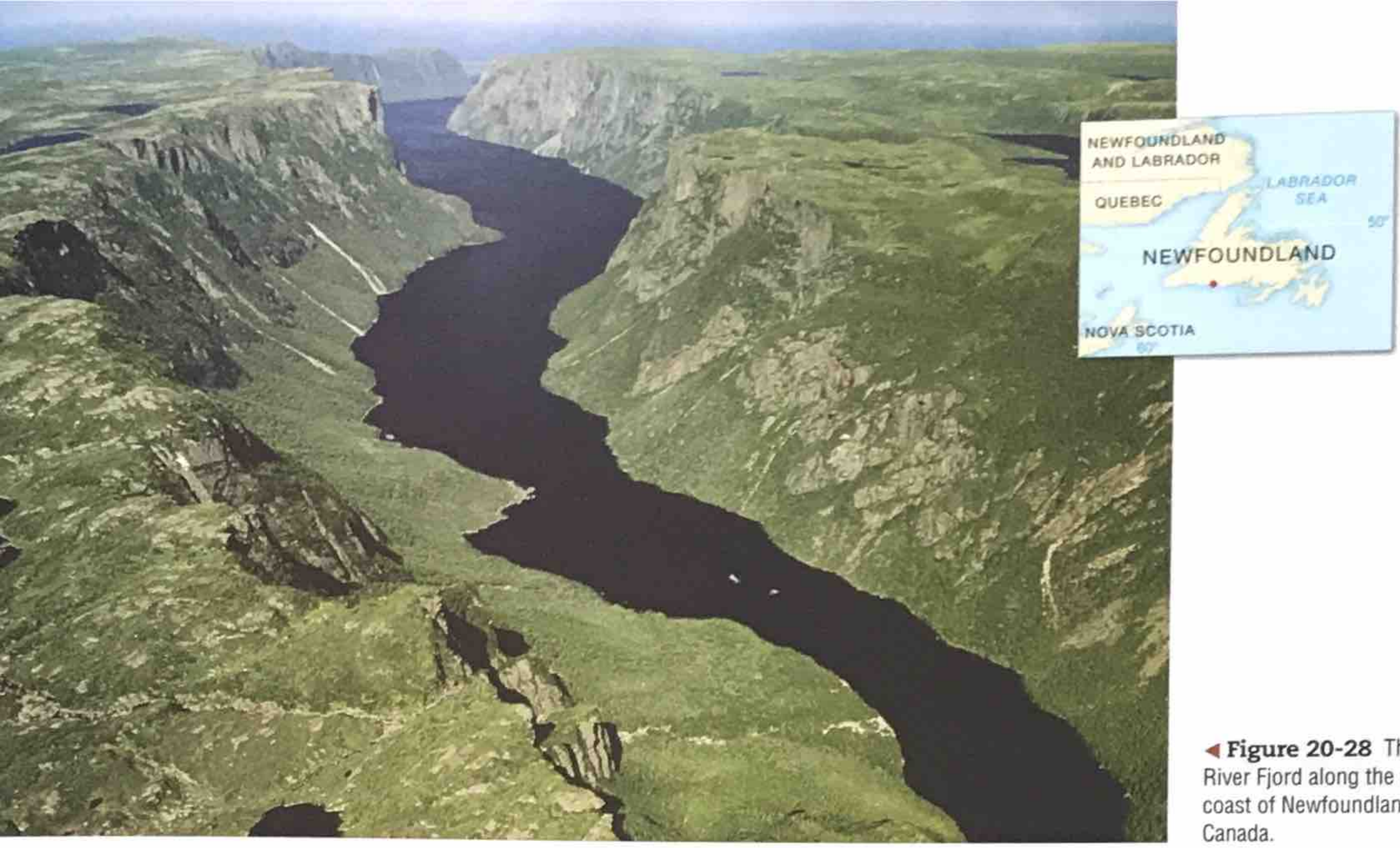
Fjorded Coasts: Spectacular coastlines often occur where high-relief coastal terrain has undergone extensive glaciation. Troughs once occupied by valley glaciers or by continental ice sheets may be so deep that their bottoms are presently far below sea level—as sea level rose at the end of the Pleistocene the troughs filled with seawater. In some localities these deep, sheer-walled coastal indentations—called **fjords**—are so numerous that they create an extraordinarily irregular coastline, often with long, narrow fingers of saltwater reaching more than 160 kilometers (100 miles) inland.

The most extensive and spectacular fjorded coasts are in Norway, western Canada, Alaska, southern Chile, the South Island of New Zealand, Greenland, and Antarctica (Figure 20-28).

Learning Check 20-10 **Why do so many coastlines around the world show signs of submergence?**



▶ **Figure 20-27** Landsat image of Chesapeake Bay. On the left, the flooded mouth of the Patuxent River can be seen running parallel to the Bay; on the right the flooded mouth of the Choptank River connects with the bay.



◀ **Figure 20-28** The Grey River Fjord along the southern coast of Newfoundland, Canada.

Coastal Emergence

FG2, FG8

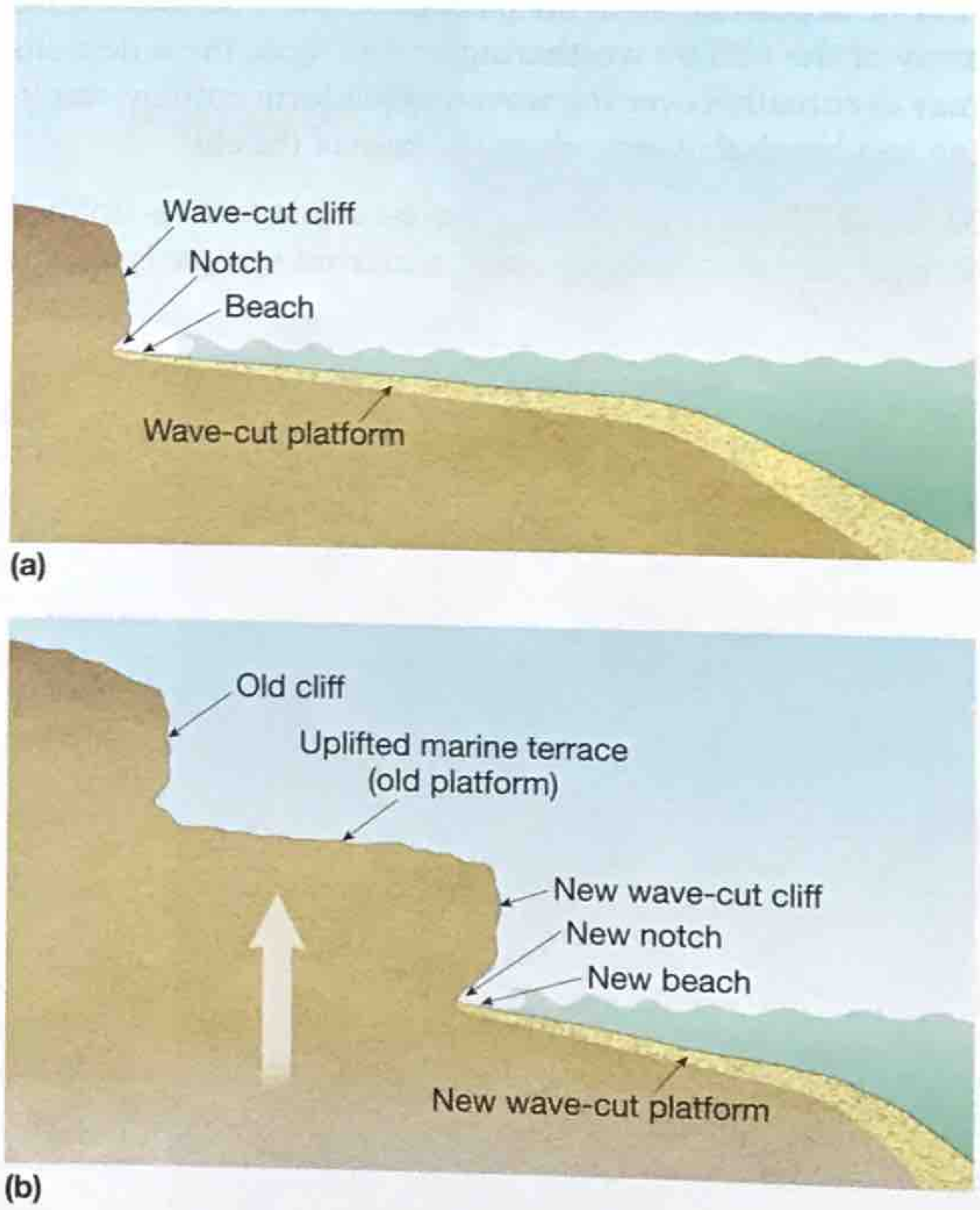
Evidence of previously higher sea levels is sometimes related to ice melting during past interglacial ages but is more often associated with tectonic uplift. The clearest topographic results of coastal emergence are shoreline features raised well above the present water level. Often the emerged portion of a continental shelf appears as a broad, flat coastal plain, with erosion wearing back the land at a cliff dropping down to the sea.

Wave-Cut Cliffs and Platforms: One of the most common coastal landform complexes comprises wave-cut cliffs, sea stacks, and wave-cut platforms (see Figure 20-11). As we discussed earlier, as waves erode away at a rocky headland, steep wave-cut cliffs are formed, and these cliffs receive the greatest pounding at their base, where the power of the waves is concentrated.

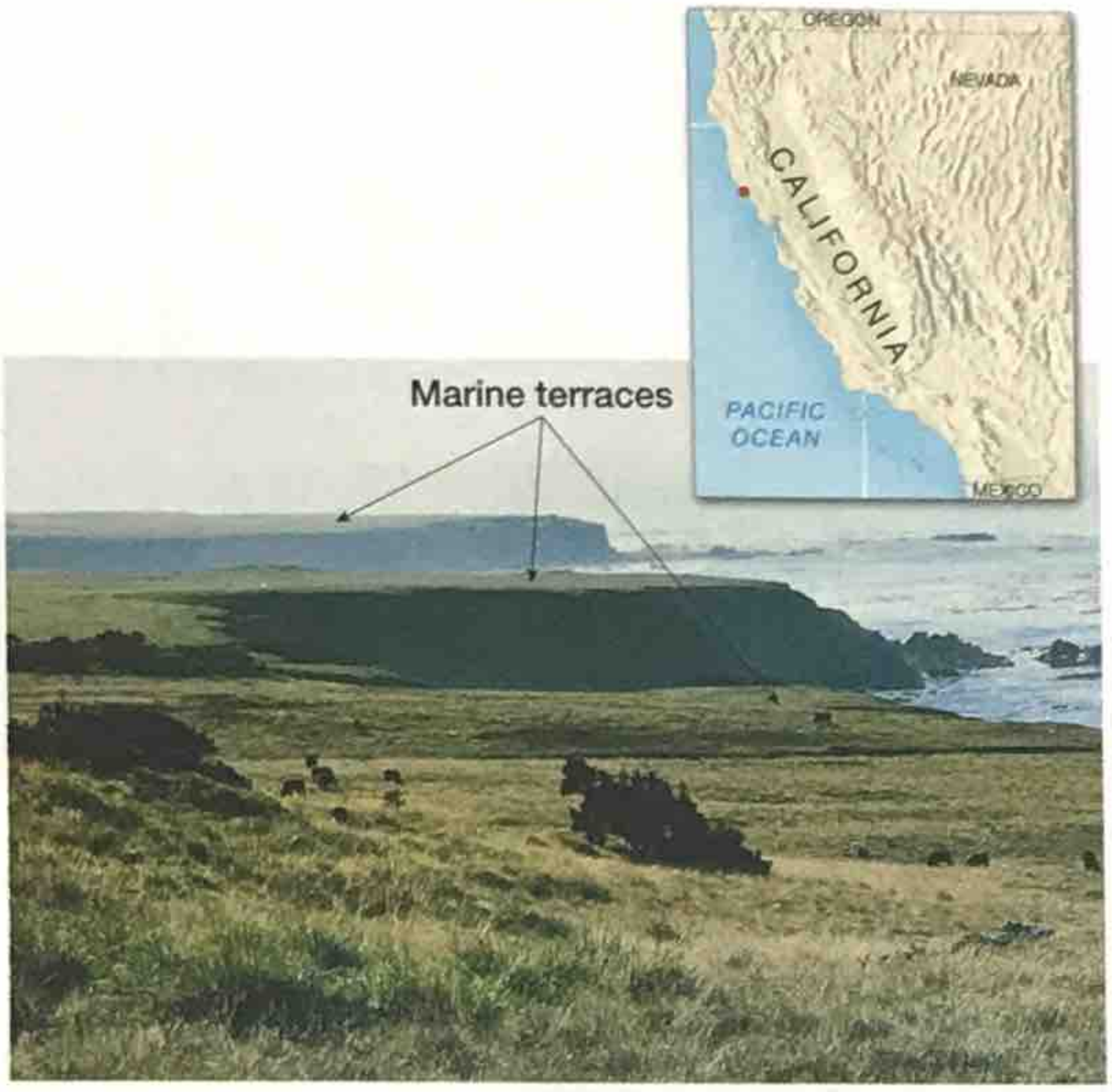
A combination of hydraulic pounding, abrasion, pneumatic push, and chemical solution at the cliff base frequently cuts a notch at the high-water level (Figure 20-29a). As the notch is enlarged, the overhang sporadically collapses, and the cliff recedes as the ocean advances. Where wave action cuts through the bottom of a cliff-topped headland, a *sea arch* may be formed (see Figure 20-6), while *sea stacks* develop where wave erosion leaves towers of rock isolated just offshore from the coastal cliff (see Figure 20-1).

Seaward of the cliff face, the pounding and abrasion of the waves create a broad erosional surface called a **wave-cut platform** (or *wave-cut bench*) usually slightly below water level. The combination of wave-cut cliff and wave-cut platform produces a profile that resembles a letter "L," with the steep vertical cliff descending to a notched base and the flat horizontal platform extending seaward.

The debris eroded from cliff and platform is mostly removed by the swirling waters. The larger fragments are battered into smaller and smaller pieces until they are small



▲ **Figure 20-29** (a) A wave-cut platform develops where a coastal cliff is worn back by wave erosion. (b) A marine terrace develops when a wave-cut platform is tectonically uplifted above sea level.



▲ **Figure 20-30** Uplifted marine terraces, well above the present shoreline. This scene is on the north coast of California near Fort Ross.

enough to be transportable. Some of the sand and gravel produced in this fashion may be washed into an adjacent bay to become, at least temporarily, a part of the beach. Much of the debris, however, is shifted directly seaward where it may be deposited. With the passage of time and the wearing away of the cliff by weathering and erosion, these deposits may eventually cover the wave-cut platform entirely, resulting in a beach that extends to the base of the cliff.

Marine Terraces: When a wave-cut platform is uplifted along a tectonically rising coast, a **marine terrace** is formed (Figure 20-29b). It appears that fluctuations of sea level during the Pleistocene played a part in the formation of at least some marine terraces: when sea level drops during a glacial period, the wave-cut platform is left well above sea level; gradual tectonic uplift during the period of low sea level leaves the terrace high enough to be preserved after sea level rises again during the subsequent interglacial period.

Along some shorelines of the world, a series of marine terraces is present, reflecting several episodes of terrace formation (Figure 20-30).

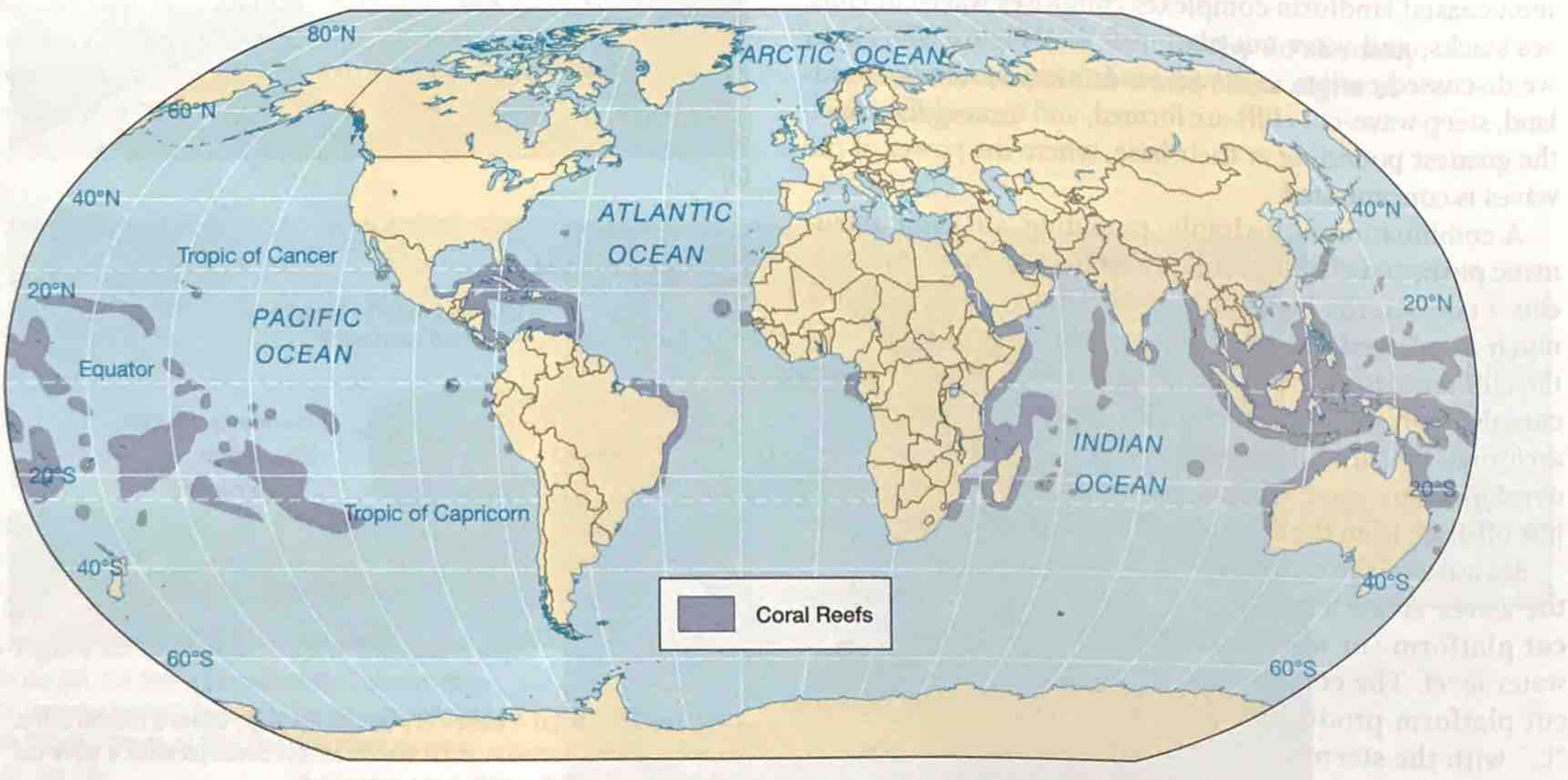
Learning Check 20-11 **What can you infer about a coastline that has a series of marine terraces?**

CORAL REEF COASTS

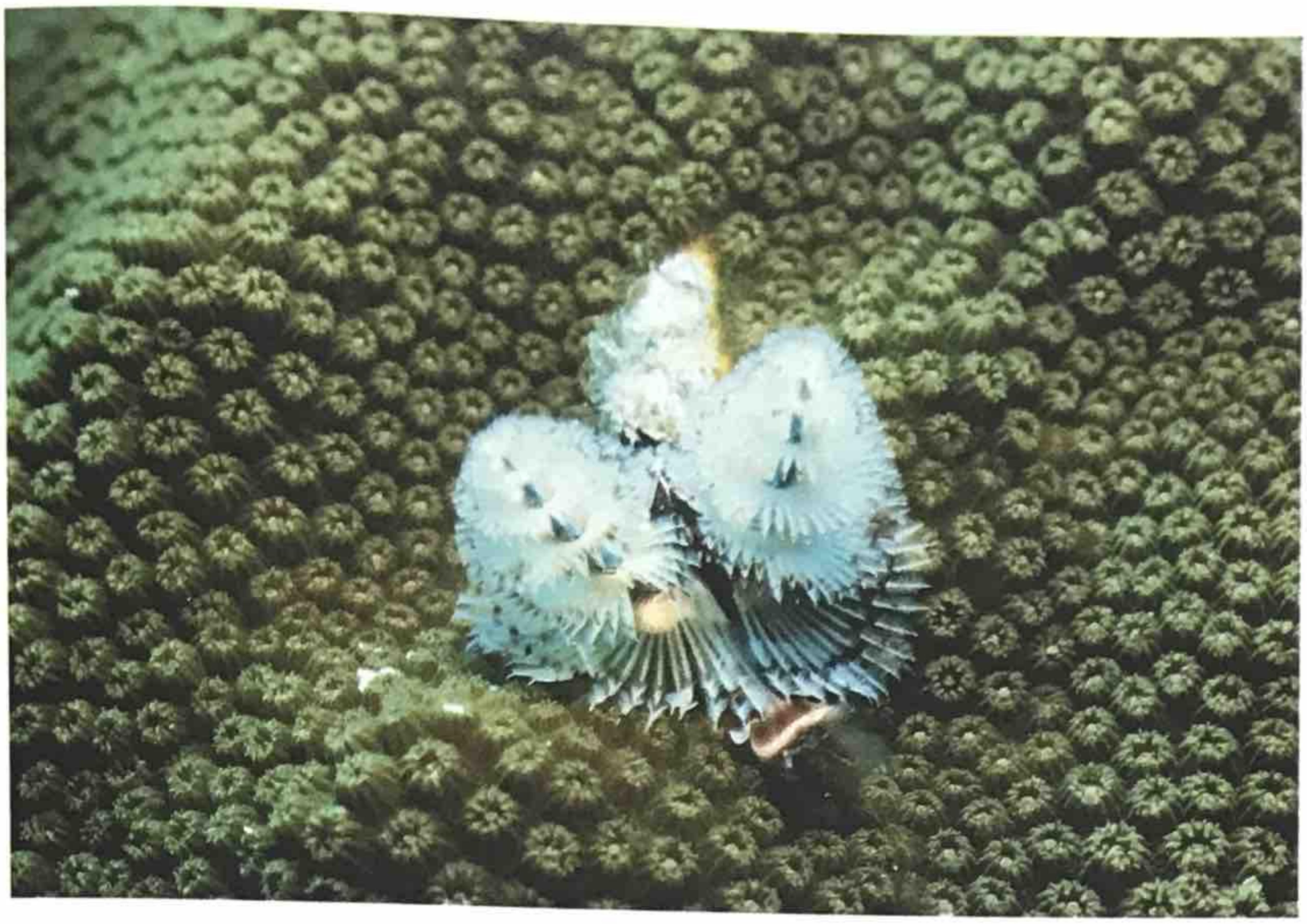
In tropical oceans, nearly all continents and islands are fringed with either *coral reefs* or some other type of coralline formation (Figure 20-31). Coralline structures are built by a complicated series of events that involve animals, algae, and various physical and chemical processes.

Coral Polyps

The critical element in the development of coral reefs is a group of anthozoan animals (members of the class *Anthozoa* that are closely related to jellyfish and sea anemones) called *stony corals*. These tiny creatures (most are only a few millimeters long) live in colonies of countless individuals, attaching themselves to one another both with living tissue and with their external skeletons (Figure 20-32). Each individual *coral polyp* extracts calcium carbonate from the seawater and secretes a limy skeleton around the lower half of its body. Most polyps withdraw into their skeletal cups during the day and extend their armlike feeding structures



▲ **Figure 20-31** Distribution of coral reefs and other coralline structures in the oceans of the world.



◀ **Figure 20-32** Coral comes in an extraordinary variety of sizes, shapes, forms, and species. This close-up reef scene in the Bahamas shows a "Christmas tree" worm in a colony of coral.

at night. At the top of the body is a mouth surrounded by rings of tentacles, which gives them a blossom-like appearance that for centuries caused biologists to believe that they were plants rather than animals. They feed on minute animal and plant plankton. Although the coral polyp is an animal, reef-building hard corals are hosts to symbiotic algae that provide additional food for the coral polyp through photosynthesis.

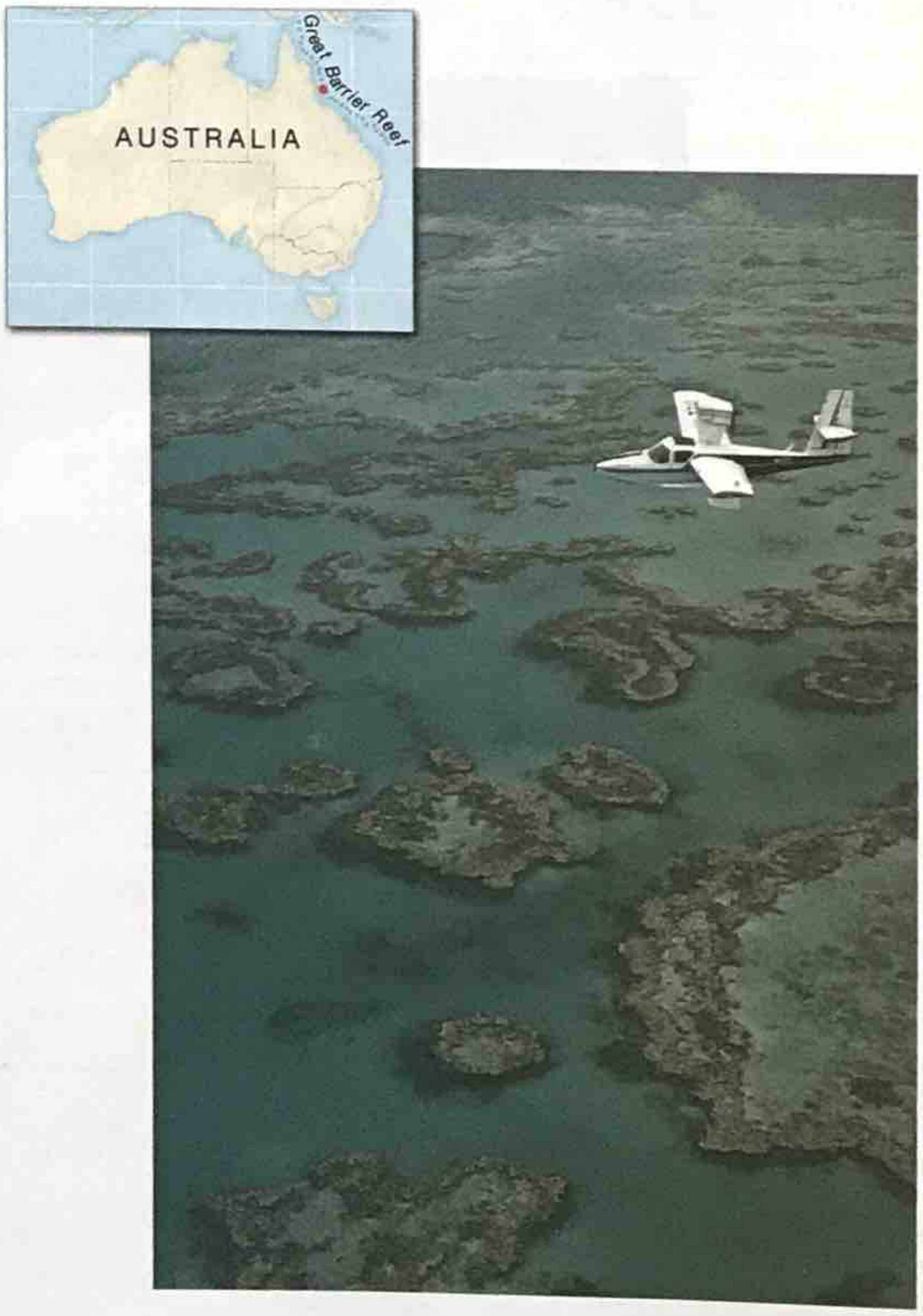
The ubiquity of coral reefs in shallow tropical waters is a tribute to the remarkable productiveness of the polyps because they are not actually very hardy creatures. They cannot survive in water that is very cool or very fresh or very dirty. Moreover, they require considerable sunlight, so most cannot live more than a few tens of meters below the surface of the ocean (recently explored *deep-* or *cold-water corals*, found at depths of more than 1000 meters [3200 feet)], are a fascinating exception to this).

Many coral reefs around the world show signs of degradation—from both natural and human-generated causes. For example, see the box, "Focus: Imperiled Coral Reefs."

Coral Reefs

Coral polyps can build coralline formations almost anywhere in shallow tropical waters where a coastline provides a stable foundation. Coral reefs in the shallows off the coasts of Florida, for instance, are built on such stable bases. The famous Great Barrier Reef off the northeastern coast of Australia is an immense shallow-water platform of bedrock largely, but not entirely, covered with coral. Its enormously complex structure includes many individual reefs, irregular coral masses, and a number of islands (Figure 20-33).

One favored location for coral reefs is around a volcanic island in tropical waters; as the volcano forms and then subsides, a sequence of different kinds of reefs may grow upward: *fringing reefs*, *barrier reefs*, and *atolls*.



▲ **Figure 20-33** A view of Australia's Great Barrier Reef.

FOCUS

Imperiled Coral Reefs

All species of reef-building coral contain zooxanthellae, a type of algae that lives in a symbiotic relationship with the coral polyp. Through photosynthesis, the algae provide nutrients to the coral—it is also the algae that give coral its beautiful color.

Coral Bleaching: For reasons that are not completely understood, when coral is stressed, it expels the algae, leaving its exoskeleton of calcium carbonate a translucent white color. This phenomenon is known as *coral bleaching* (Figure 20-F). In some cases, bleached corals die within just a few weeks if the zooxanthellae are not replaced.

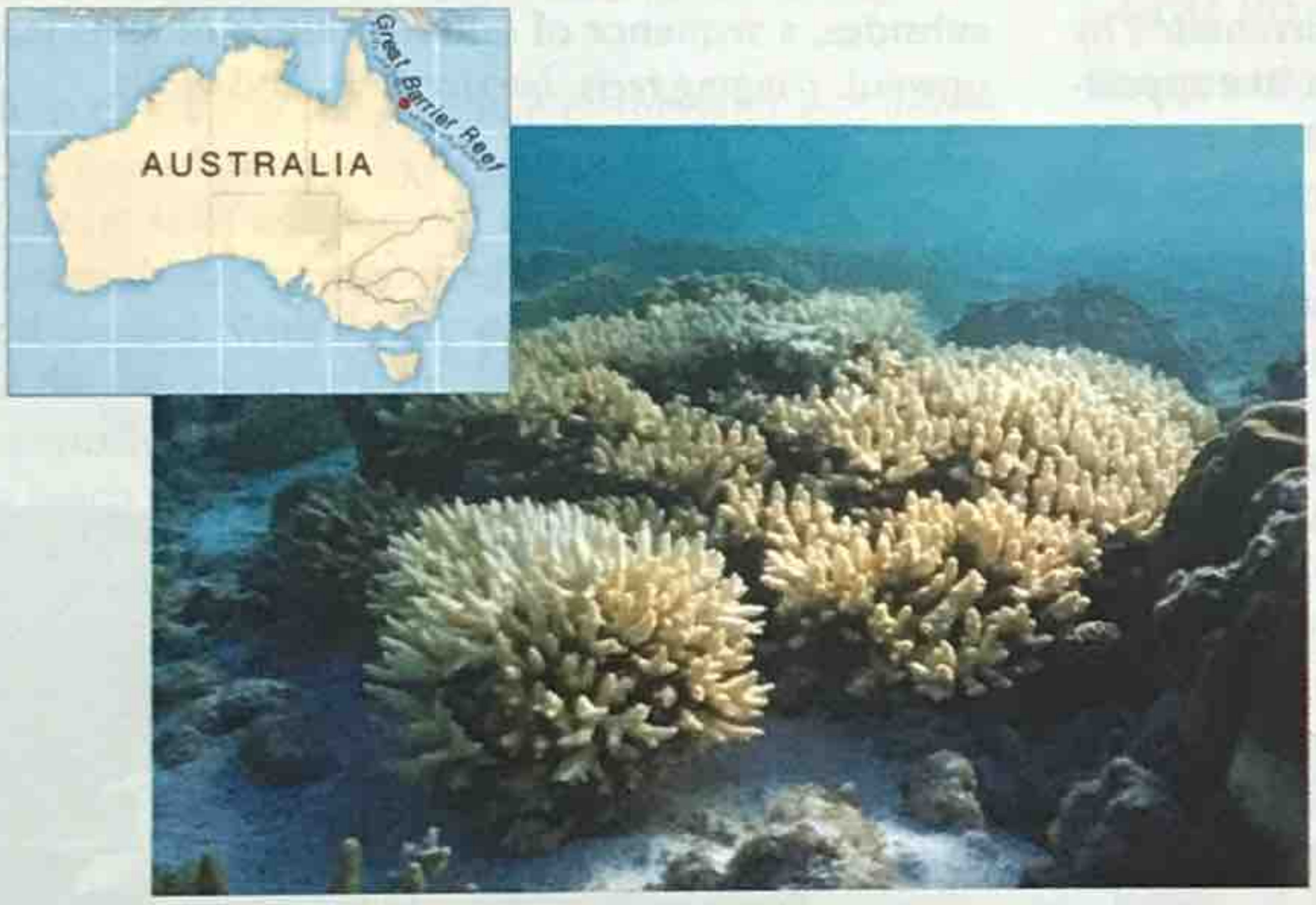
Bleaching events have been observed for decades, caused by such factors as a sharp decrease in water salinity, sedimentation, pollution, and abrupt changes in temperature; but it became clear to researchers in the 1980s that stress from high water temperature was the most common cause. The warming of coastal waters during the 1982–83 El Niño was observed to cause coral bleaching in Panama; the 1997–98 El Niño was even stronger and caused bleaching in reefs around the world.

In recent years, some researchers have started pointing to higher sea-surface temperatures (SST) associated with climate change warming as at least one of the causes of the rising number of coral bleaching incidents. In 2010, a major bleaching event associated with high SST occurred in the Indian Ocean and the coral reefs of Southeast Asia; scientists at the Australian Research Council reported that it may be the worst coral die-off ever documented.

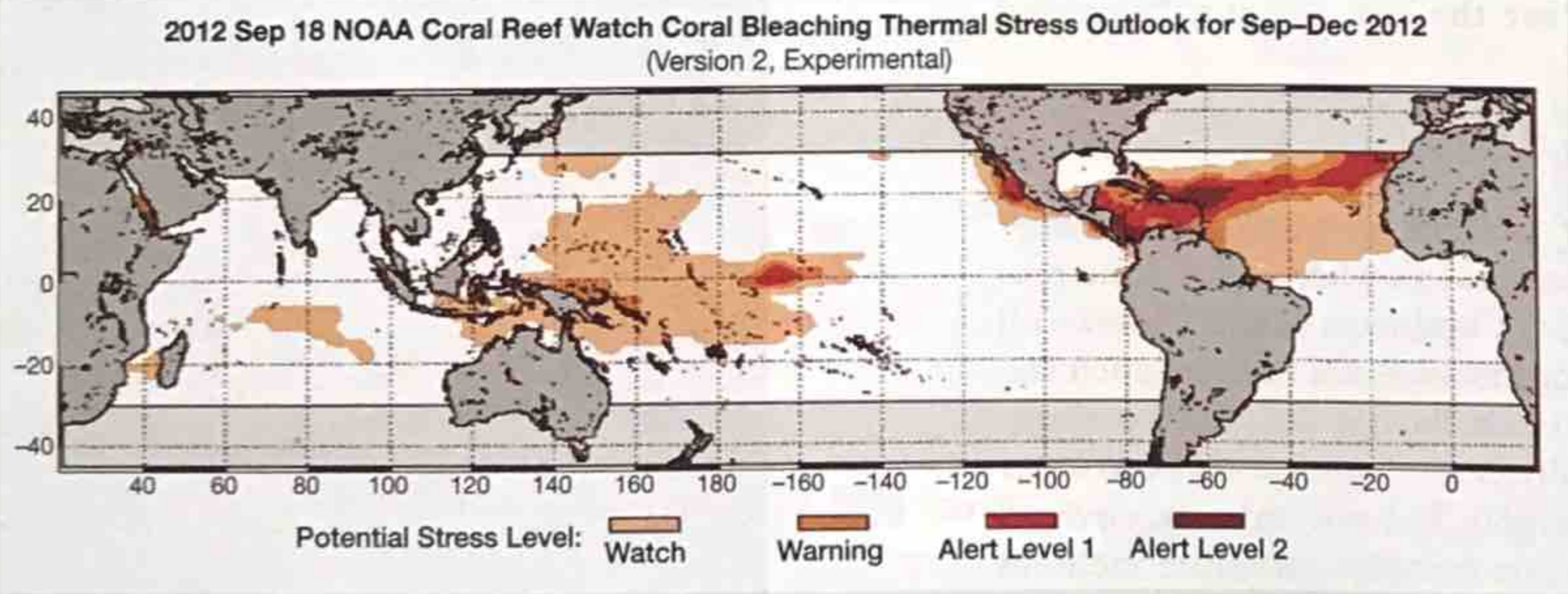
Monitoring Coral Bleaching: The National Oceanic and Atmospheric Administration (NOAA) monitors stress on coral reefs through its Coral Reef Watch program. NOAA is currently testing a Bleaching Outlook system that issues predictions of bleaching potential for periods of up to three months based on experimental SST forecasts (Figure 20-G).

Acidification of Oceans: In addition to bleaching, coral reefs are being stressed by the slight acidification of the ocean waters caused by the absorption of carbon dioxide (acidification of the oceans is discussed in Chapter 9). In January 2009, an international panel of 155 marine scientists issued the Monaco Declaration, stating that damage from ocean acidification is already detectable, and that with the projected increase in atmospheric carbon dioxide—and the associated increased acidification of the ocean—many regions of the world will become "chemically inhospitable" to coral reefs by midcentury.

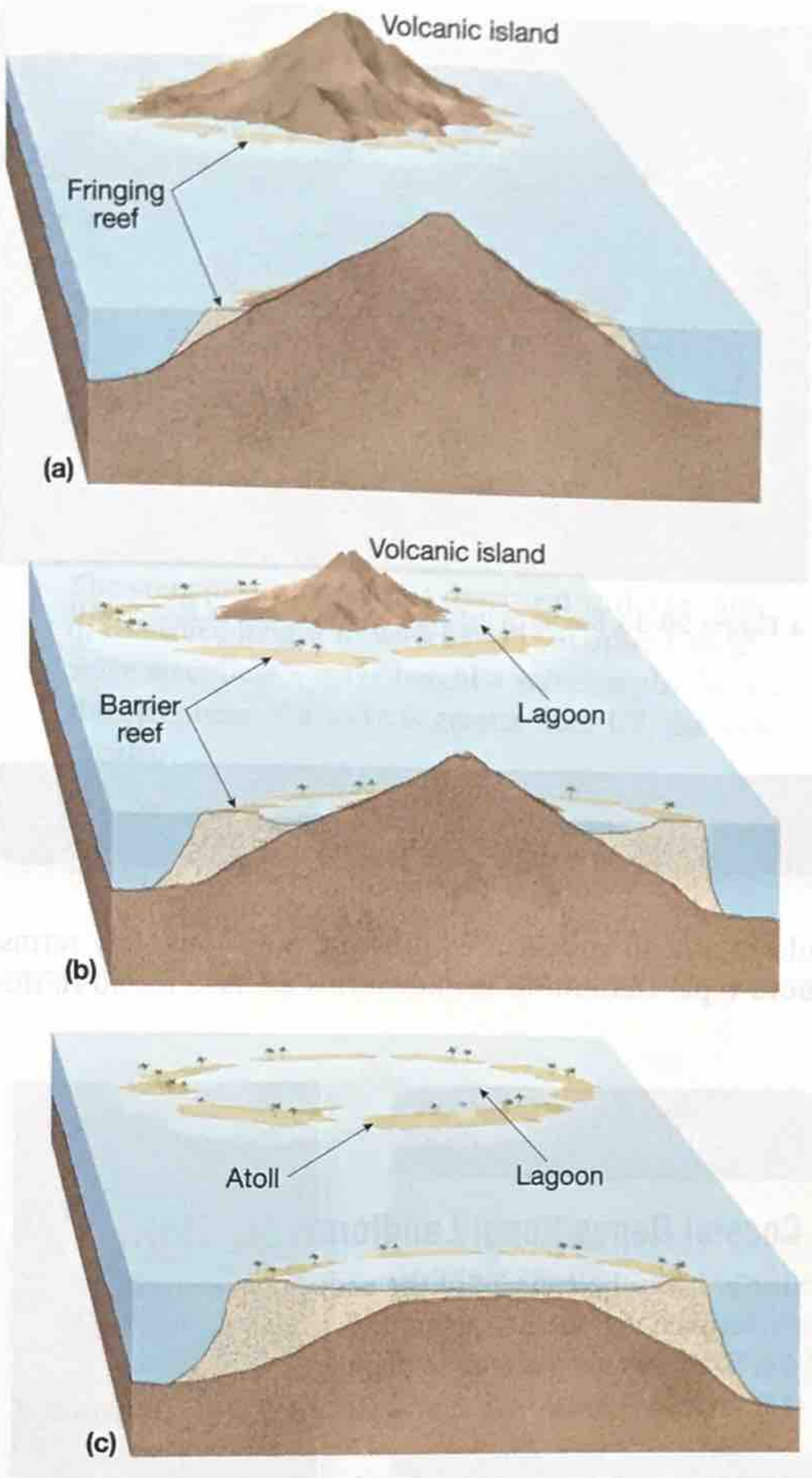
Ecosystem Loss: The loss of coral reefs through bleaching and other natural and human-produced causes is alarming many researchers. When coral dies, an entire ecosystem is at risk: the fish and other creatures that depend on coral for survival are stressed, local fisheries can decline, the protection from storm waves offered to low-lying islands fringed with reefs is diminished, and, of course, the loss of species and biodiversity may be irreparable.



▲ **Figure 20-F** Bleached coral in the Great Barrier Reef, Australia.



▲ **Figure 20-G** Coral Reef Watch experimental Coral Bleaching Thermal Stress Outlook for fall 2012. The darker the shade of red, the higher the potential for coral bleaching.



◀ **Figure 20-34** Coral reef formation around a sinking volcano. (a) Around a newly formed volcano rising above the water of a tropical ocean, secretions from coral polyps living along the shallow-water flanks of the volcano accumulate into a fringing reef attached to the mountain. (b) As the volcano becomes dormant and begins to sink, the coral continues to grow upward over the original base, essentially a cylinder surrounding the mountain. Such a reef separated from its mainland by a lagoon is a barrier reef. (c) Once the volcano is completely submerged, the coral surrounding a landless lagoon is called an atoll reef.

Animation
Seamounts & Coral Reefs

Fringing Reefs: When the volcano first forms, as, for example, over the Hawaiian hot spot described in Chapter 14, coral accumulates on the part of the mountain flank just below sea level because it is in these shallow waters that polyps live. The result is a reef built right onto the volcano, as shown in Figure 20-34a; such an attached reef is called a **fringing reef** (Figure 20-35). As the plate moves off the hot spot it cools and becomes denser, so the volcano begins to sink.

Barrier Reefs: As new layers are laid down over old, the coral builds upward around the volcano as a cylinder of irregular height. At the same time, the volcano is sinking and pulling the original reef base downward. When the coral has been built up enough and the volcano has sunk enough, the result at the water surface is a coral ring separated by a lagoon from the part of the volcano still above water, as in Figure 20-34b. Called a **barrier reef**, this ring of coral may be a broken circle because of the varying thickness of the coral, appearing to "float" around a central volcanic peak (but, of course, is actually attached to the flanks of the sinking mountain far below the water surface). The surface of a barrier reef is usually right at sea level, with some portions projecting upward into the air.

▶ **Figure 20-35** A part of the fringing reef on the island of Moorea in French Polynesia.

Atolls: Coral polyps continue to live in the upper, shallow-water portions of a barrier reef, and so the reef continues to grow upward. Once the top of the volcano sinks below the water surface, the reef surrounding a now landless lagoon is called an **atoll** (Figure 20-34c). The term *atoll* implies a ring-shaped structure. In actuality, however, the ring is rarely unbroken; rather it consists of a string of closely spaced coral islets separated by narrow channels of water. Each individual islet is called a *motu*. Because coral cannot live above sea level, much of the coral debris that makes up the above-water portion of an atoll has been deposited there by storm waves (Figure 20-36).

▲ **Figure 20-36** Bassas da India is a coral atoll west of Madagascar.

Learning Check 20-12 **How can an atoll develop from a fringing reef or a barrier reef?**

Chapter 20 LEARNING REVIEW

After studying this chapter, you should be able to answer the following questions. Key terms from each text section are shown in **bold type**. Definitions for key terms are also found in the glossary at the back of the book.

KEY TERMS AND CONCEPTS

Coastal Processes (*p. 574*)

1. What are some of the ways that landform development along ocean shorelines is different from that along lakeshores?

Waves (*p. 575*)

2. How are most ocean waves generated?
3. What are **swells** in the ocean?
4. How is a **wave of oscillation** different from a **wave of translation**?
5. Contrast the characteristics of ocean waves in deep water with waves in shallow water, especially note how **wavelength** and **wave height** change as a wave comes onshore.
6. Contrast **swash** and **backwash** on a beach.
7. Describe and explain the process of **wave refraction**.
8. Explain the formation and characteristics of a **tsunami**.

Important Shoreline-Shaping Processes (*p. 579*)

9. Why did **eustatic sea-level changes** take place during the Pleistocene?
10. What is the source of most sediment along the shorelines of the continents?
11. Describe the formation and characteristics of **longshore currents**.
12. Describe the process of **beach drifting**.

Coastal Depositional Landforms (*p. 585*)

13. Explain the concept of the **sediment budget** of a coastal depositional landform such as a beach.
14. What causes a **beach** to change shape and size?
15. Describe and contrast a coastal **spit** and a **baymouth bar**.
16. Under what circumstances does a **tombolo** form?
17. Describe the features of a **barrier island**.
18. What happens to most coastal **lagoons** with the passage of time?
19. How do **groins** and **jetties** typically affect the beaches around them?

Shorelines of Submergence and Emergence (*p. 590*)

20. Explain the formation of **ria shorelines** and **fjords**.
21. Explain how wave-cut cliffs and **wave-cut platforms** develop.
22. Describe the formation of a **marine terrace** along a shoreline of emergence.

Coral Reef Coasts (*p. 592*)

23. Explain how a coral **fringing reef** forms and how it can subsequently become transformed first to a **barrier reef** and then to an **atoll**.

STUDY QUESTIONS

1. What factors influence the erosional power of waves striking a coastline?
2. How does air serve as a tool of erosion in wave action?
3. What will likely happen to a downcurrent beach when a major river flowing into the ocean is dammed? Why?
4. What is beach nourishment, and is it a good investment for a coastal community? Why or why not?
5. Why are shorelines of submergence so common today?
6. How might global warming and other environmental changes caused by human activities affect coral reefs?

EXERCISES

1. The steepness of a wave is described with the ratio of the wave height to wavelength (in other words: wave steepness = wave height ÷ wavelength). When the steepness of a wave is greater than 1/7, the wave breaks.
   a. What is the maximum wave height for a wavelength of 7 meters? _____ meters
   b. What is the maximum wave height for a wavelength of 20 meters? _____ meters
   c. If a breaking wave is 2 meters high, what is the wavelength? _____ meters
2. As a rough generalization, most waves will break when they reach a water depth that is 1.3 times the wave height.
   a. If a breaking wave has a height of 1.5 meters, how deep is the water below? _____ meters
   b. If a breaking wave has a height of 7 meters, how deep is the water below? _____ meters

Seeing Geographically

Look again at the photograph of the Big Sur coastline at the beginning of the chapter (p. 572). What explains the way the waves approach shore? The distance from shore where waves break varies along this stretch of coastline—why? Where along this coastline is wave erosion strongest? Why is this so? Where does it appear that most of the coastal sediment is being deposited? What explains this?

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