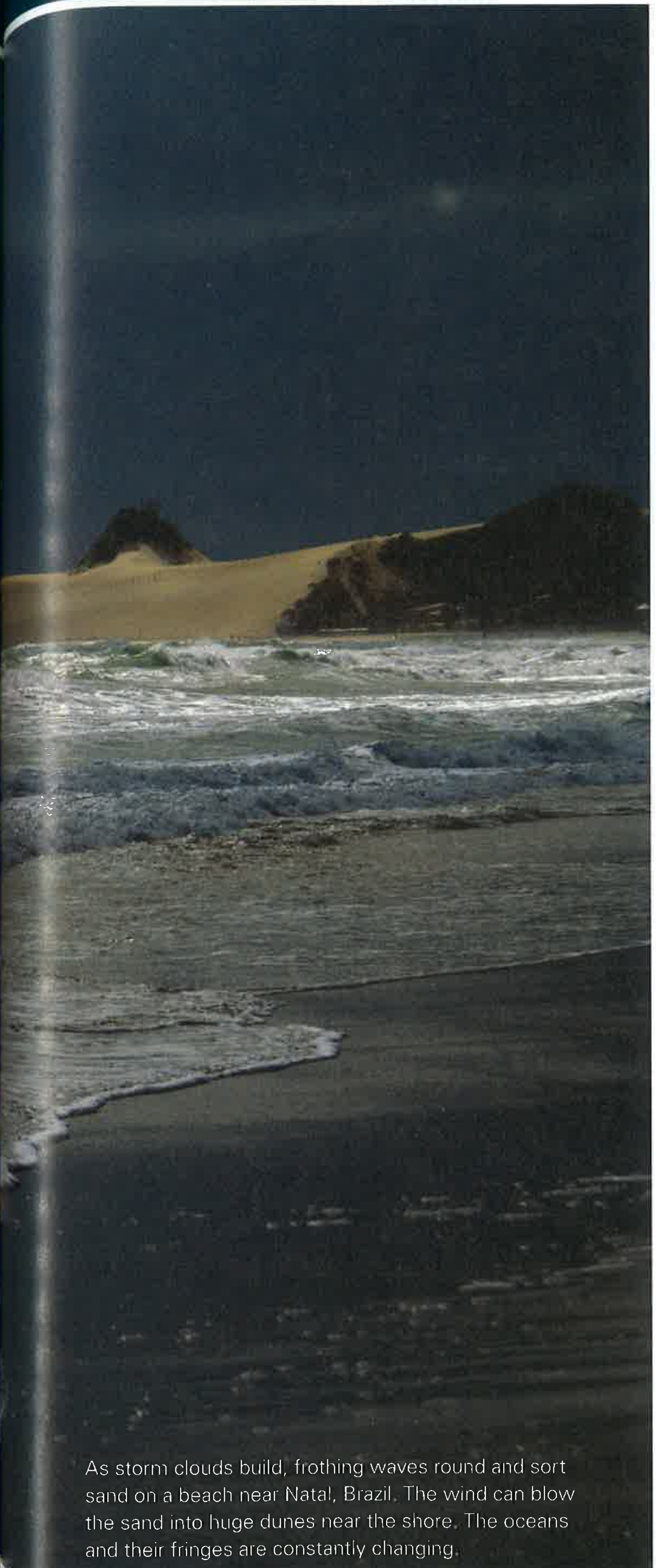


As storm clouds build, frothing waves round and sort sand on a beach near Natal, Brazil. The wind can blow the sand into huge dunes near the shore. The oceans and their fringes are constantly changing.

Chapter Objectives

By the end of this chapter, you should know . . .

- how tectonic processes produce bathymetric features of the sea floor.
- the nature and causes of surface and deep currents.
- the behavior and cause of tides.
- why waves form and how they behave.
- how a great variety of different coastal landforms develop and evolve.
- how changes in sea level, wave erosion, and human activities affect the coast.

"The three great elemental sounds in nature are the sound of rain, the sound of wind in a primeval wood, and the sound of the outer ocean on a beach."

—Henry Beston (American naturalist, 1888–1968)

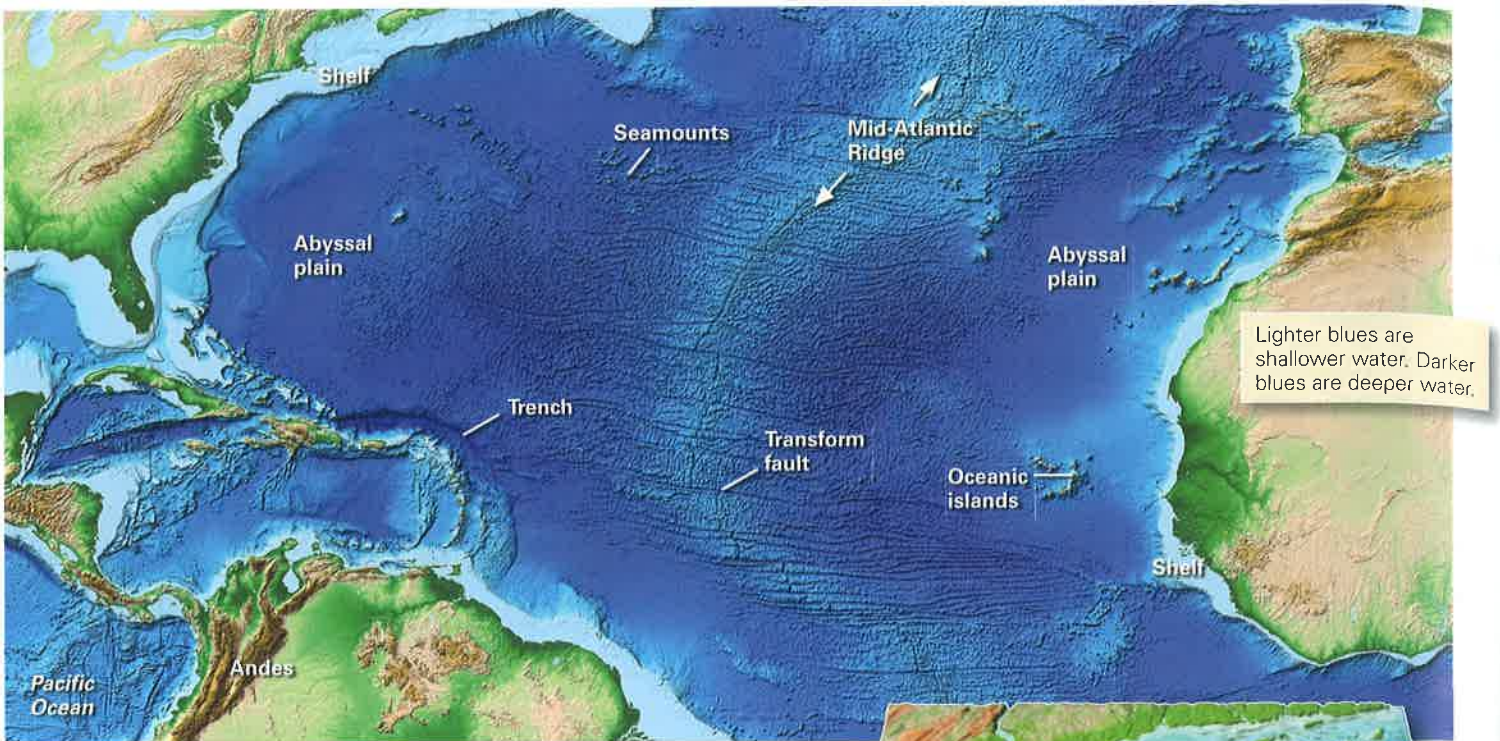
15.1 Introduction

When seen from space, Earth glows blue, for the ocean covers 70.8% of its surface (**Fig. 15.1**). The ocean provides the basis for life, tempers Earth's climate, and spawns its storms. It is a vast reservoir for water and chemicals that cycle into the atmosphere and crust, and for sediment washed off the continents. In this chapter, we first learn the fundamental geologic characteristics of ocean basins, the nature of seawater, and the pattern of ocean circulation. Then we focus on the landforms that develop along the **coast**, the region where the land meets the sea. Finally, we consider the hazards of coastal areas and how people confront them.

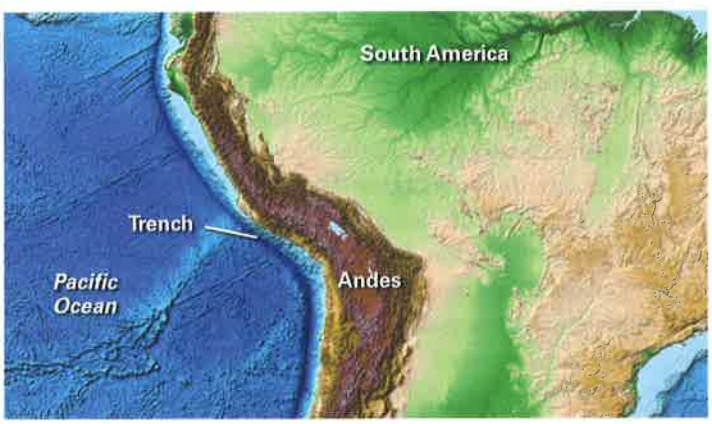
15.2 Landscapes Beneath the Sea

If the surface of the lithosphere were completely smooth, an ocean would surround the Earth as a uniform, 2.5-km-deep layer. But because about 30% of this planet's surface is dry land, most seawater resides in distinct ocean basins (**Fig. 15.2a**). The distinction between land and sea exists because continental and oceanic lithosphere differ markedly from one another in terms of composition and thickness

FIGURE 15.3 Bathymetric features of the seafloor. The maps are produced by computer using measurements from satellites or submersibles.



(a) Passive margins occur on both sides of the Atlantic. Active margins border the Caribbean and the western coast of South America.



(b) The western coast of South America is an active continental margin.

(c) A submarine canyon off the coast of New Jersey. Turbidity currents in submarine canyons carry sediment to the abyssal plain.

sea level are called **seamounts**. Particularly voluminous eruptions have produced broader buildups of basalt that are known as submarine plateaus.

Take-Home Message

Ocean basins exist because oceanic and continental lithosphere differ. Sea-floor bathymetric features (ridges, trenches, and fracture zones) reflect plate-tectonic processes. Abyssal plains overlie old lithosphere, and continental shelves overlie passive-margin basins.

15.3 Ocean Water and Currents

Composition and Temperature

If you've ever had a chance to swim in the ocean, you may have noticed that you float much more easily in ocean water than you do in freshwater. That's because ocean water contains an average of 3.5% dissolved salt; in contrast, typical freshwater contains less than 0.02% salt. The dissolved ions fit between water molecules without changing the volume of the water, so adding salt to water increases the water's density, and you float higher in a denser liquid.

There's so much salt in the ocean that if all the water suddenly evaporated, a 60-m-thick layer of salt would coat the ocean floor. This layer would consist of about 75% halite (NaCl) with lesser amounts of gypsum ($CaSO_4 \cdot H_2O$), anhydrite

($CaSO_4$), and other salts. Oceanographers refer to the concentration of salt in water as **salinity**. Although ocean salinity averages 3.5%, measurements from around the world demonstrate that salinity varies with location, ranging from about 1.0% to about 4.1%. Salinity reflects the balance between the addition of freshwater by rivers or rain and the removal of freshwater by evaporation, for when seawater evaporates, salt stays behind; salinity also depends on water temperature, for warmer water can hold more salt in solution than can cold water.

When the *Titanic* sank after striking an iceberg in the North Atlantic, most of the unlucky passengers and crew who jumped or fell into the sea died within minutes because the seawater temperature at the site of the tragedy approached freezing, and cold water removes heat from a body very rapidly. Yet swimmers can play for hours in the Caribbean, where sea-surface temperatures reach 28°C (83°F). Though the *average* global sea-surface temperature hovers around 17°C, it ranges between freezing near the poles to almost 35°C in restricted tropical seas. The correlation of average temperature with latitude exists because the intensity of solar radiation varies with latitude.

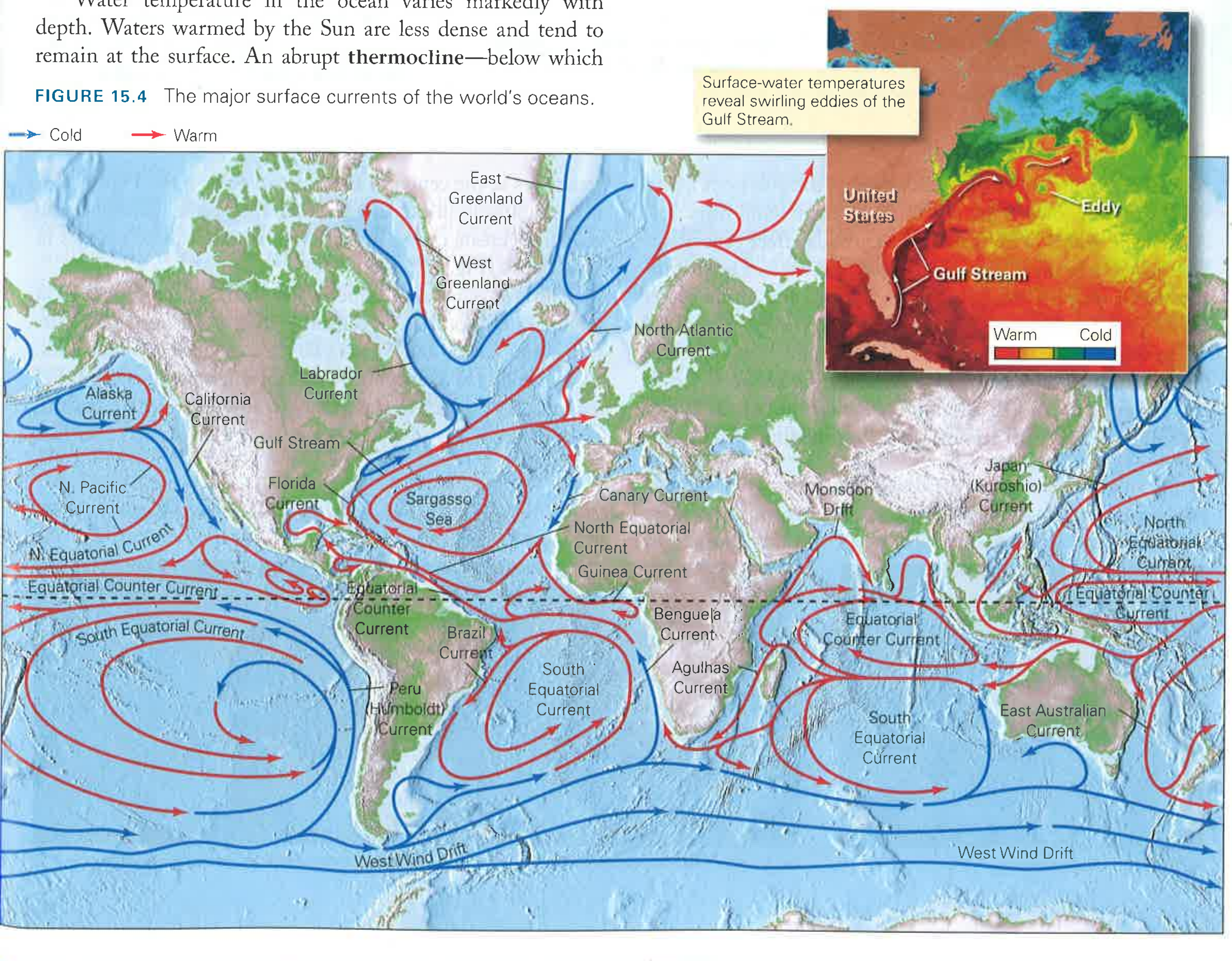
Water temperature in the ocean varies markedly with depth. Waters warmed by the Sun are less dense and tend to remain at the surface. An abrupt **thermocline**—below which water temperatures decrease sharply, reaching near freezing at the sea floor—appears at a depth of about 300 m in the tropics. There is no pronounced thermocline in polar seas, since surface waters there are already so cold.

Currents: Rivers in the Sea

Since first setting sail on the open ocean, people have known that the water of the ocean does not stand still, but rather flows or circulates at velocities of up to several kilometers per hour in fairly well-defined streams called **currents**. Oceanographic studies demonstrate that circulation in the sea occurs at two levels: *surface* currents affect the upper hundred meters of water, and *deep* currents keep the remainder of the water column in motion.

Surface currents occur in all the world's oceans (**Fig. 15.4**). They result from interaction between the sea surface and the wind—as moving air molecules shear across the surface of the water, the friction between air and water drags the water along with it. The Earth's rotation, however, generates the **Coriolis effect** (**Box 15.1**), a phenomenon that causes surface currents in the northern hemisphere to veer

FIGURE 15.4 The major surface currents of the world's oceans.

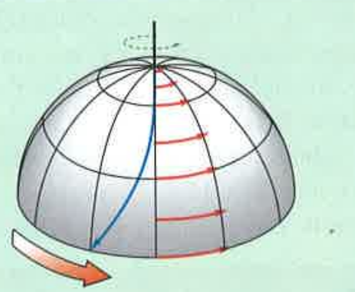


BOX 15.1 CONSIDER THIS . . .

The Coriolis Effect

Imagine that you have a huge cannon—aim it due south and fire a projectile from the North Pole to a target on the equator (**Fig. Bx15.1a**). If the Earth were standing still, the shot would follow a line of longitude. But the Earth isn't standing still. It rotates counterclockwise around its "axis" (an imaginary line that passes through the planet's center and its geographic poles). To an observer in space, an object at the pole doesn't move at all as the Earth spins because it is sitting on the axis, but an object at the equator moves at about 1,665 km/h (1,035 mph). Because of this difference, the target on the equator will have moved by the time the projectile reaches it. In fact, to an observer standing on the Earth and moving with it, the projectile follows a curving trajectory. The same phenomenon happens if you place the cannon on the equator and fire the projectile due north (**Fig. Bx15.1b**)—the projectile's path curves because the projectile moves eastwards progressively faster than the land beneath while moving north. (The same phenomenon, of course, happens in the southern hemisphere, but in reverse.) This behavior is called the Coriolis effect, after the French engineer who, in 1835, described its consequences. Because of the Coriolis effect, north-flowing currents in the northern hemisphere deflect to the east, and south-flowing currents deflect to the west.

FIGURE Bx15.1 The Coriolis effect occurs because the velocity of a point at the equator, in the direction of the Earth's spin, is greater than that of a point near the pole.



(a) A projectile shot from the pole to the equator deflects to the west.

(b) A projectile shot from the equator to the pole deflects to the east.

toward the right and surface currents in the southern hemisphere to veer toward the left of the average wind direction. Across the width of an ocean, the Coriolis effect causes surface currents to make a complete loop, known as a **gyre**. Surface water may become trapped for a long time in the center of the gyre, where currents hardly exist, so these regions tend to accumulate floating plastics, sludge, and seaweed. The "Sargasso Sea," named for a kind of floating seaweed, lies at the center of the North Atlantic gyre, and the "Great Pacific Garbage Patch," an accumulation of floating plastic and trash, lies at the center of the North Pacific gyre. Figure 15.4 is a simplification of currents—interactions of currents with coastlines create chains of eddies, in which water circulates in small loops (**Fig. 15.5a–c**).

Surface water and deeper water in the ocean exchange at a number of locations. Specifically, in *downwelling* zones, surface water sinks, and in *upwelling* zones, deeper water rises. Downwelling and upwelling occur for a number of reasons. For example, in places where winds blow surface water shoreward, an oversupply of water develops along the coast, so surface

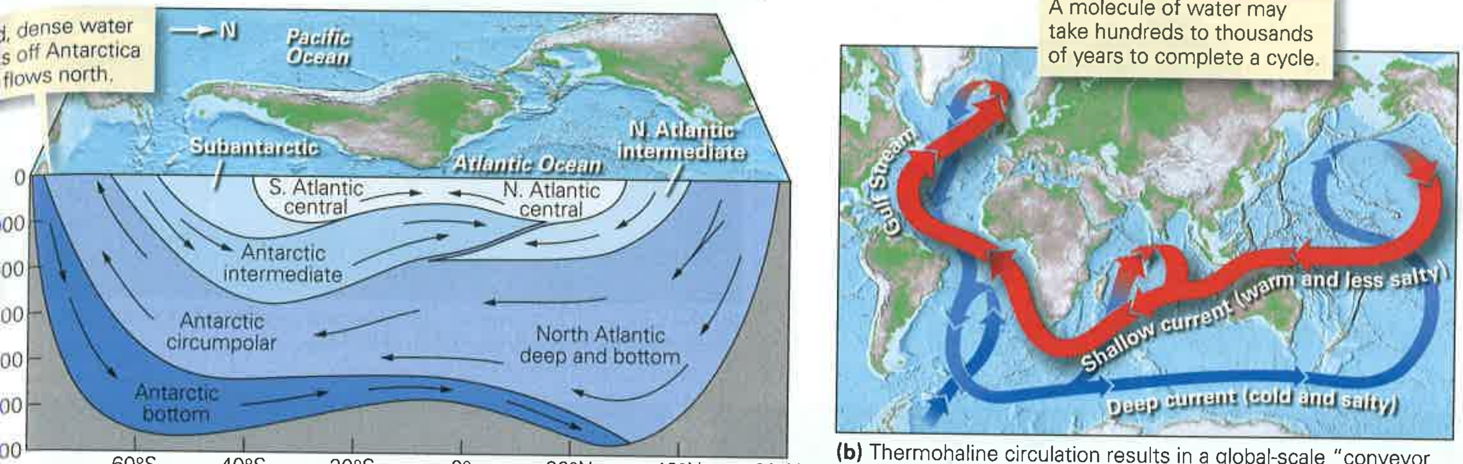
FIGURE 15.5 The complexity of the ocean's currents. An animation by NASA, based on data collected over a two-year period, shows the details of eddies and swirls in the ocean, and emphasizes that currents interact with the coasts.

(a) Western Indian Ocean.

(b) Southern Ocean, south of Africa

(c) Western North Atlantic, and Caribbean.

FIGURE 15.6 Global-scale upwelling and downwelling of ocean water.



(a) Due to variations in density, the oceans are stratified into distinct water masses.

(b) Thermohaline circulation results in a global-scale "conveyor belt" that circulates water throughout the entire ocean system. The ocean mixes entirely in a 1,500-year period.

water must sink to make room. And where winds blow surface water away from the shore, a deficit of water develops along the coast, so deeper water must rise to fill the gap. Upwelling of deeper water also occurs near the equator, where winds blow steadily from east to west, because the Coriolis effect deflects surface currents to the right in the northern hemisphere and to the left in the southern hemisphere, thereby leading to the development of a water deficit along the equator. The resulting rise of cool, nutrient-rich water fosters an abundance of life in equatorial water.

Contrasts in water density, caused by differences in temperature and salinity, can also drive upwelling and downwelling. We refer to the rising and sinking of water driven by such density contrasts as **thermohaline circulation**. During thermohaline circulation, denser (cold and/or saltier) water sinks, whereas water that is less dense (warm and/or less salty) rises. As a result, the cold water in polar regions sinks and flows back along the bottom of the ocean toward the equator. This process divides the ocean vertically into a number of distinct water masses, which mix only very slowly with one another. In the Atlantic Ocean, for example, the Antarctic Bottom Water sinks along the coast of Antarctica, and the North Atlantic Deep Water sinks in the north polar region (**Fig. 15.6a**). The combination of surface currents and thermohaline circulation, like a conveyor belt, moves water and heat among the various ocean basins and moderates global climate (**Fig. 15.6b**).

Take-Home Message

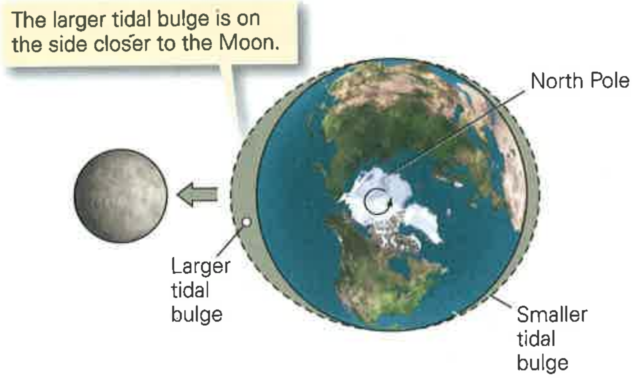
Ocean salinity and temperature vary with depth and location. The wind drives surface currents, forming large gyres. Upwelling and downwelling develop due to wind-driven water surplus or deficit, or due to density variations related to temperature and salinity.

15.4 Tides

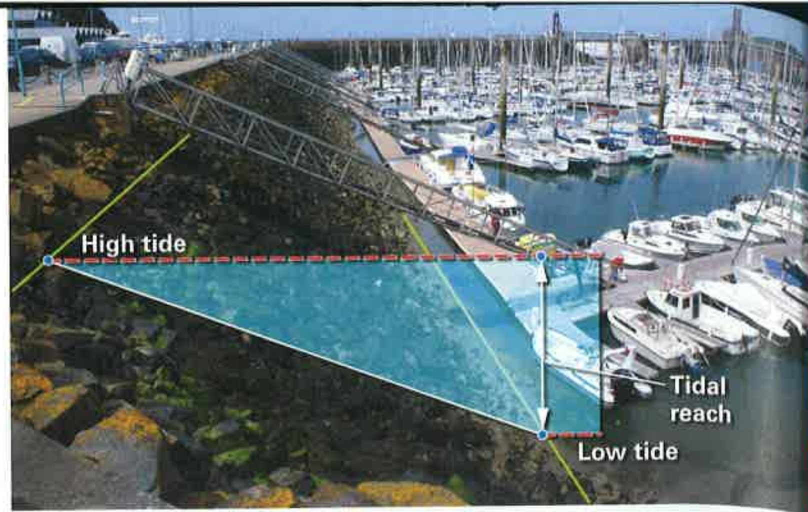
A ship captain hoping to set sail from a port must pay close attention to the **tide**, the generally twice daily rise and fall of sea level. At high tide, the harbor's water is deep enough that the ship can easily float over obstacles, but at low tide, the water may be so shallow that the ship could run aground. Tides develop in response to the *tide-generating force*, which in simple terms is due in part to the gravitational attraction of the Sun and Moon, and in part to centrifugal force produced by the revolution of the Earth-Moon System around its center of mass. The tide-generating force results in two tidal bulges in the oceans on opposite sides of our planet (**Fig. 15.7a**). Of these, the larger one occurs on the side of the Earth closer to the Moon, for the Moon's gravitational pull is stronger than that of other contributors to the tide-generating force. When a location lies under a tidal bulge, it experiences a high tide, and when it underlies a depression between two bulges, it experiences a low tide. If the Earth's surface were smooth and completely submerged beneath the oceans, each point on the surface would experience two high tides and two low tides per day, as the Earth spins relative to the tidal bulges. But the complex shape of the sea floor near the shore means that the specific timing and magnitude of tides can vary along a coast. Specifically, the **tidal reach**, meaning the elevation difference between sea level at high tide and low tide, can range from less than a meter to several meters. The largest tidal reach on Earth, 16.8 m (54.6 ft), occurs in the Bay of Fundy on the Atlantic coast of Canada.

The manifestation of tides along a shore depends not only on the tidal reach, but on the slope of the shore. Along a vertical cliff, the intertidal zone (the region of shore submerged at high tide and exposed at low tide) appears as a ring of stained,

FIGURE 15.7 Ocean tides and their manifestation.



(a) Tides develop as the Earth spins relative to the two tidal bulges.



(b) The tidal reach is the vertical distance between low tide and high tide. This photo of a French harbor was taken at low tide.

(c) Mont Saint-Michel, off the western coast of France, is an island at high tide.

(d) At low tide, muddy tidal flats surround Mont Saint-Michel.

barnacle- and seaweed-encrusted rock. Where the coast has a gentle slope, the shoreline (meaning the boundary between land and sea) moves substantially inland during a rising tide, and seaward during a falling tide (**Fig. 15.7b**). Vast muddy tidal flats may be exposed during low tide (**Fig. 15.7c, d**). Tidal flats can be hazardous for people who head out across the mud flats in search of shellfish, for the rising tide can trap them offshore.

Take-Home Message

Gravitational attraction by the Moon and Sun, as well as centrifugal force in the Earth-Moon System, cause two tidal bulges that move around the Earth. Because of the twice daily rise and fall of tides, intertidal regions are alternately submerged and exposed.

15.5 Wave Action

Wind-driven waves make the ocean surface a restless, ever-changing vista. They develop because of the shear between the molecules of air in the wind and the molecules of water at the surface of the sea. Molecules of water within a wave moving across the open ocean don't move great distances horizontally but rather move in a circle. The diameter of the circle is largest for molecules at the surface, where it equals the wave height (the vertical distance from crest to trough) of the wave. With increasing depth, though, the diameter of the circle decreases until, at a depth equal to about half the wavelength (the horizontal distance between two wave troughs or two wave crests), there is no wave movement at all (**Fig. 15.8a**). Submarines traveling below this **wave base** cruise through smooth water, while ships toss about above.

The character of waves in the open ocean depends on the strength of the wind (how fast the air moves) and on the fetch of the wind (the distance over which it blows). When the wind first begins to blow, it creates ripples in the water surface, pointed waves whose height and wavelength are small. With continued blowing over a long fetch, swells, larger waves with wave heights of 2 to 10 m and wavelengths of 40 to 500 m, begin to build. Hurricane wave heights may grow to over 35 m. Swells may travel for thousands of kilometers across the ocean, well beyond the region where they formed.

The constructive interference of waves (meaning the additive effect that happens when two wave crests cross each other), the interaction of waves and currents, and the focusing of wave energy due to the shape of the sea floor can lead to the growth of **rogue waves**, defined as waves that are two to five times the size of most of the large waves passing a locality in a given time interval. Rogue waves have swamped the decks of ocean liners.

Did you ever wonder . . .
why the breakers that surfers love form near the shore?

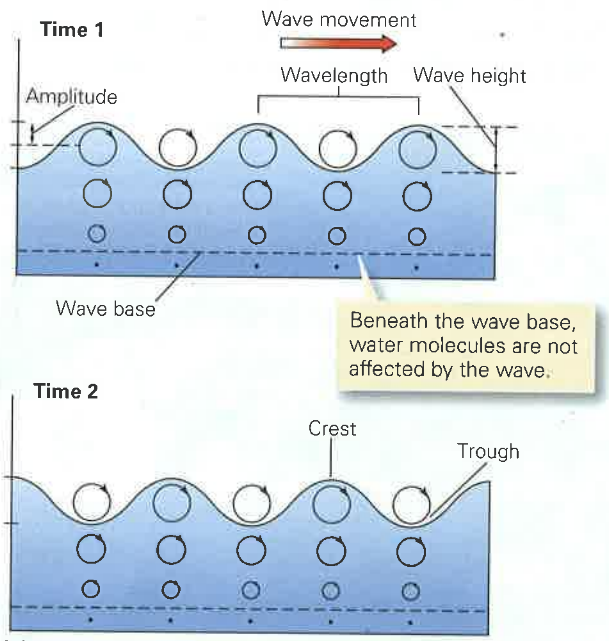
Waves have no effect on the ocean floor, as long as the floor lies below the wave base. However, near the shore, where the wave base just touches the floor, it causes a slight back-and-forth motion of sediment. Closer to shore, as the water gets shallower, friction between the wave and the sea floor slows the deeper part of the wave, and the motion in the wave becomes more elliptical (**Fig. 15.8b**). Eventually, water at the top of the wave curves over the base, and the wave becomes a breaker, ready for surfers to ride. Breakers crash onto the shore in the surf zone, sending a surge of water up the beach. This upward surge, or **swash**, continues until friction brings motion to a halt. Then gravity draws the water back down the beach as **backwash**.

Waves may make a large angle with the shoreline as they're coming in, but they bend as they approach the shore, a phenomenon called **wave refraction**; right at the shore, wave crests generally make less than a 5° angle with the shoreline (**Fig. 15.9a, b**). To understand why this happens, imagine a wave approaching the shore so that its crest initially makes an angle of 45° with the shoreline. The end of the wave closer to the shore touches bottom first and slows down because of friction, whereas the end farther offshore continues to move at its original velocity, swinging the whole wave around so that it becomes more parallel with the shoreline.

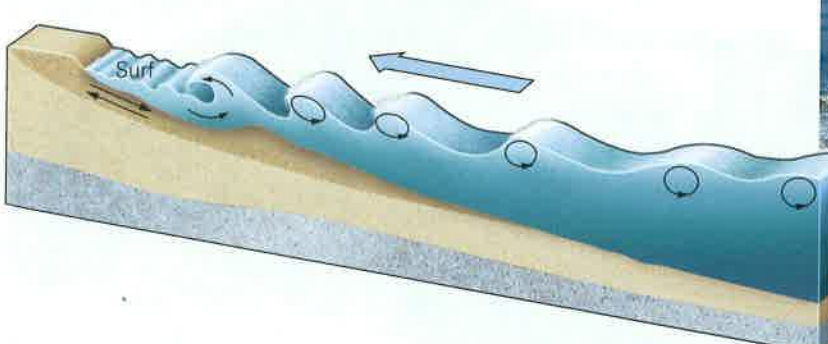
Although wave refraction decreases the angle at which waves move close to shore, it does not necessarily eliminate the angle. Where waves do arrive at the shore obliquely, water in the nearshore region has a component of motion that trends parallel to the shore. This **longshore current** causes swimmers floating in the water just offshore to drift gradually in a direction parallel to the beach. And where waves roll onto the shore at an angle, sediment in the surf follows a sawtooth pattern of movement that results in a gradual *net* transport of beach sediment parallel to the beach—such movement of sediment is called **longshore drift** (or beach drift). This sawtooth pattern happens because the swash of a wave moves perpendicular to the wave crest, so an oblique wave carries sediment diagonally up the beach, but the backwash must flow straight down the slope of the beach due to gravity.

Waves pile water up on the shore incessantly. As the excess water moves back to the sea, it may localize into a strong seaward flow perpendicular to the beach called a rip current. Rip

FIGURE 15.8 Ocean waves build in response to the shear of wind blowing over the water surface.



(a) Within a deep-ocean wave, water molecules follow a circular path. The radius of the circle decreases with depth. Note that the wave height is twice the amplitude.



(b) As the wave approaches shore, friction slows its base. Water motion in the wave becomes more elliptical, and the wave becomes a breaker.

currents are the cause of many drownings every year along beaches, because they can carry unsuspecting swimmers far away from the beach.

> **Take-Home Message**
>
> The friction of the wind against the sea surface causes waves to form. Within a wave, water moves in a circle; the amount of motion decreases with depth. Near shore, water piles up into breakers that refract when they approach the shore, causing longshore drift.

15.6 Where Land Meets Sea: Coastal Landforms

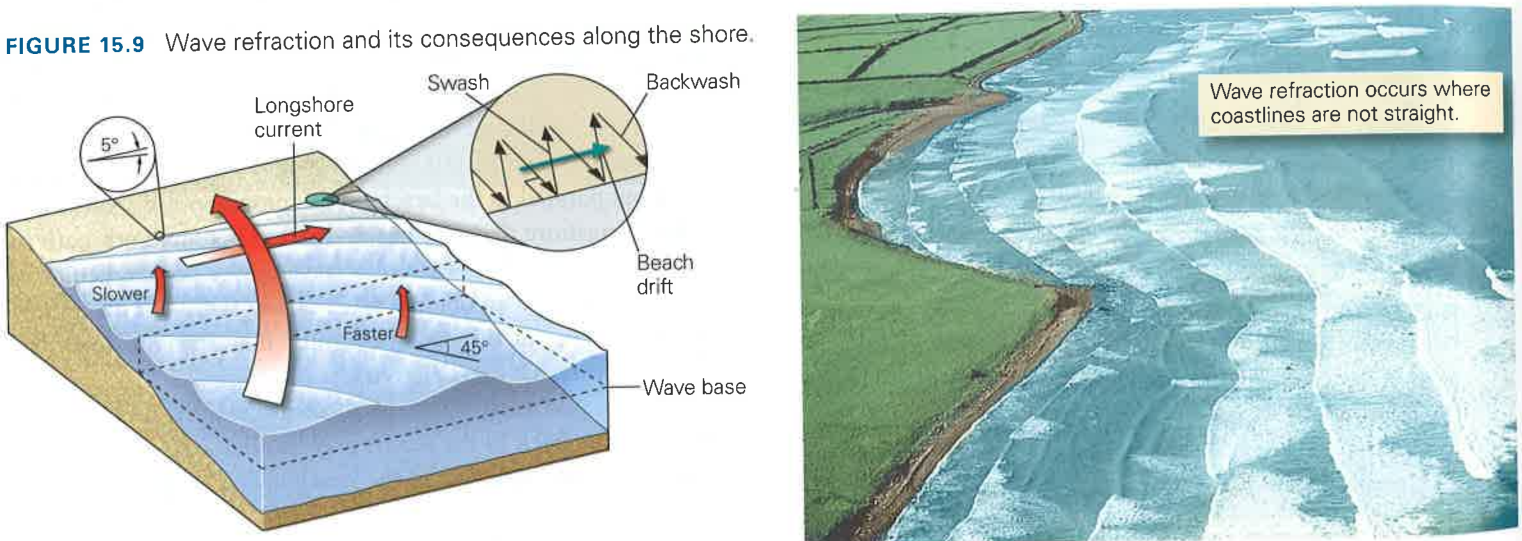
Tourists along the Amalfi coast of Italy thrill to the sound of waves crashing on rocky shores. But in the Virgin Islands sunbathers can find seemingly endless white sand beaches, and along the Mississippi delta, vast swamps border the sea. Large, dome-like mountains rise directly from the sea in Rio de Janeiro, Brazil, but a 100-m-high vertical cliff marks the boundary between the Nullarbor Plain of southern Australia and the Great Southern Ocean. As these examples illustrate, **coasts**, the belts of land bordering the sea, vary dramatically in terms of topography and associated landforms.

Beaches and Tidal Flats

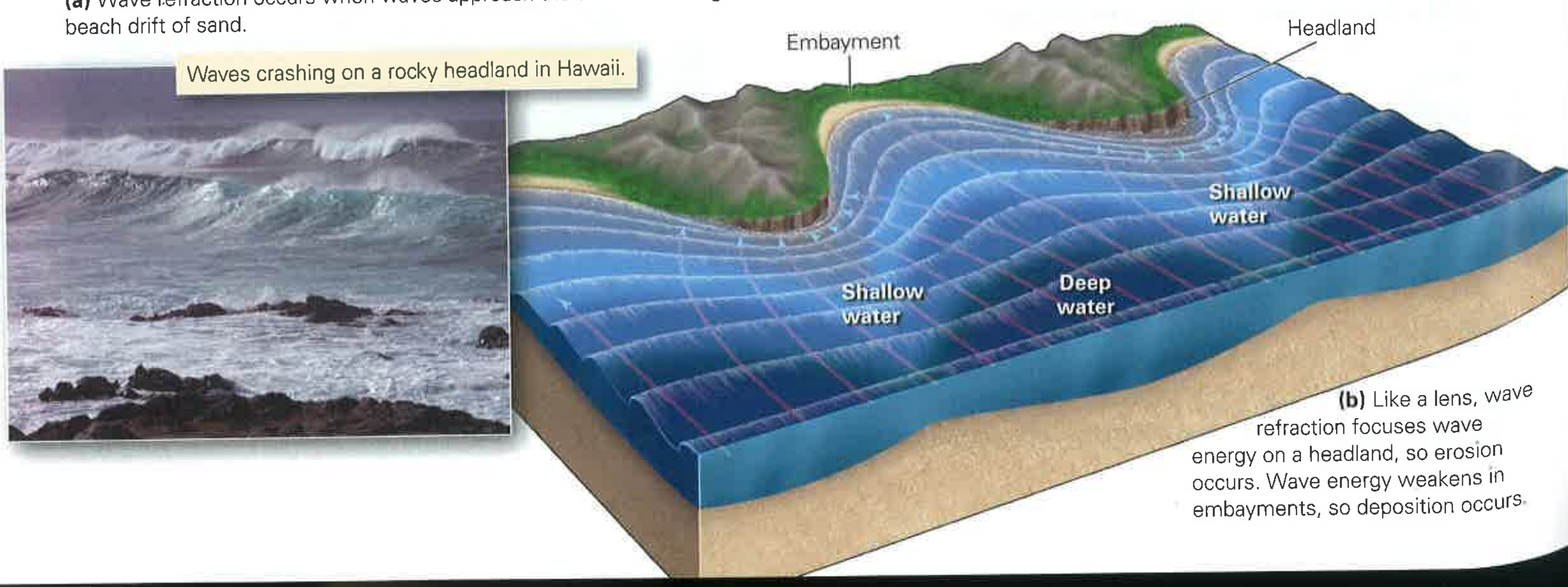
For millions of vacationers, the ideal holiday includes a trip to a **beach**, a gently sloping fringe of sediment along the shore. Some beaches consist of pebbles or boulders, whereas others consist of sand grains (**Fig. 15.10a, b**). This is no accident, for waves winnow out finer sediment like silt and clay and carry it to quieter water, where it settles. Storm waves, which can smash cobbles against one another with enough force to shatter them, have little effect on sand, for sand grains can't collide with enough energy to crack. Thus, cobble beaches exist only where nearby cliffs supply large rock fragments.

> **Did you ever wonder . . .**
> why beautiful sandy beaches don't form along all coasts?

FIGURE 15.9 Wave refraction and its consequences along the shore.



(a) Wave refraction occurs when waves approach the shore at an angle. If the wave reaches the beach at an angle, it causes a longshore current and beach drift of sand.

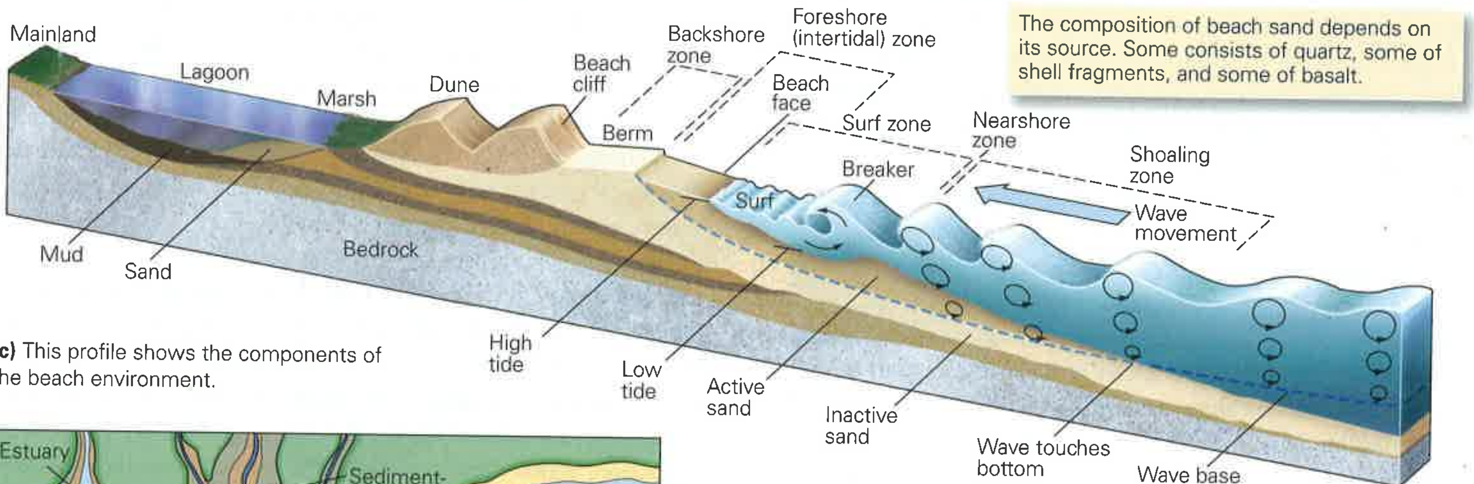


(b) Like a lens, wave refraction focuses wave energy on a headland, so erosion occurs. Wave energy weakens in embayments, so deposition occurs.

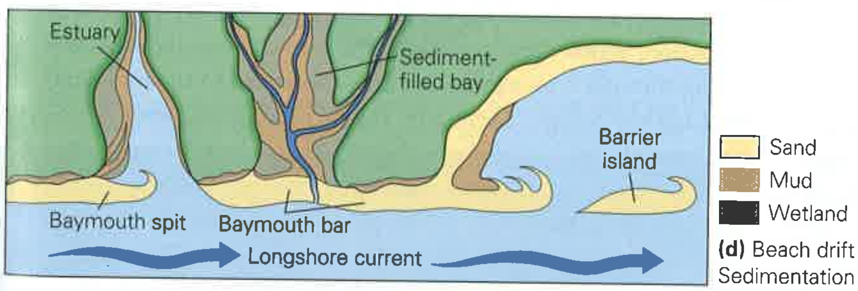
FIGURE 15.10 Characteristics of beaches, barrier islands, and tidal flats.

(a) A gravel beach along the Olympic Peninsula, Washington. The clasts were derived from erosion of adjacent cliffs.

(b) A sand beach on the western coast of Puerto Rico. Wave action has carried away finer sediment.



(c) This profile shows the components of the beach environment.



(d) Beach drift can generate sand spits and baymouth bars. Sedimentation eventually fills in the region behind a baymouth bar.

(e) A satellite image showing barrier islands off the coast of North Carolina.

(f) At low tide, boats at anchor rest in the mud of a tidal flat along the coast of Wales.

The composition of sand varies from beach to beach, because different sands come from different sources. Sands derived from the weathering and erosion of silicic-to-intermediate rocks consist mainly of quartz; other minerals in these rocks chemically weather to form clay, which washes away in waves. Beaches made from the erosion of limestone, or of coral reefs and shells, consist of carbonate sand, including masses of sand-sized chips of shells. And beaches derived from the erosion of basalt boast black sand, made of tiny basalt grains.

A *beach profile*, a cross section drawn perpendicular to the shore, illustrates the shape of a beach (**Fig. 15.10c**). Starting from the sea and moving landward, a beach consists of a foreshore zone, or intertidal zone, across which the tide rises and falls. The beach face, a steeper, concave-up part of the foreshore zone, forms where the swash of the waves actively scours the sand. The backshore zone extends from a small step, cut by high-tide swash to the front of the dunes or cliffs that lie farther inshore. The backshore zone includes one or more berms, horizontal to landward-sloping terraces that receive sediment only during a storm.

Geologists commonly refer to beaches as "rivers of sand," to emphasize that beach sand moves along the coast over time—it is not a permanent substrate. Wave action at the shore moves an active sand layer on the sea floor on a daily basis. Inactive sand, buried below this layer, moves only during severe storms or not at all. Longshore drift, discussed earlier, can transport sand hundreds of kilometers along a coast in a matter of centuries. Where the coastline indents landward, beach drift stretches beaches out into open water to create a **sand spit**. Some sand spits grow across the opening of a bay, to form a baymouth bar (**Fig. 15.10d**).

The scouring action of waves sometimes piles sand up in a narrow ridge away from the shore called an **offshore bar**, which parallels the shoreline. In regions with an abundant sand supply, offshore bars rise above the mean high-water level and become **barrier islands** (**Fig. 15.10e**), and the water between a barrier island and the mainland becomes a quiet-water **lagoon**, a body of shallow seawater separated from the open ocean. Though developers have covered some barrier islands with expensive resorts, in the time frame of centuries to millennia, barrier islands are temporary features and may wash away in a storm.

Tidal flats, regions of clay and silt exposed or nearly exposed at low tide but totally submerged at high tide, develop in regions protected from strong wave action (**Fig. 15.10f**). They are typically found along the margins of lagoons or on shores protected by barrier islands. Here, sediments accumulate to form thick, sticky layers.

Rocky Coasts

More than one ship has met its end, smashed and splintered in the spray and thunderous surf of a rocky coast, where bedrock cliffs rise directly from the sea. Lacking the protection of a beach, rocky coasts feel the full impact of ocean breakers. The water pressure generated during the impact of a breaker can pick up boulders and smash them together until they shatter, and it can squeeze air into cracks, creating enough force to push rocks apart. Further, because of its turbulence, the water hitting a cliff face carries suspended sand and thus can abrade the cliff. The combined effects of shattering, wedging, and abrading, together called wave erosion, gradually undercut a cliff face and make a **wave-cut notch** (**Fig. 15.11a**). Undercutting continues until the overhang becomes unstable and breaks away at a joint, creating a pile of rubble at the base of the cliff that waves immediately attack and break up. In this process, wave erosion cuts away at a rocky coast, so that the cliff gradually migrates inland. Such cliff retreat may leave behind a **wave-cut bench**, or *platform*, that becomes visible at low tide (**Fig. 15.11b**).

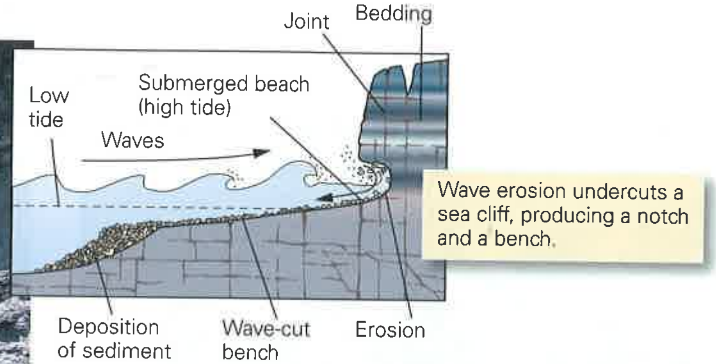
Other processes besides wave erosion break up the rocks along coasts. For example, salt spray coats the cliff face above the waves and infiltrates into pores. When the water evaporates, salt crystals grow and push apart the grains, thereby weakening the rock. Biological processes also contribute to erosion, for plants and animals in the intertidal zone bore into the rocks and gradually break them up.

Many rocky coasts are irregular with headlands protruding into the sea and embayments set back from the sea. Wave energy focuses on headlands and disperses in embayments, a result of wave refraction. The resulting erosion removes debris at headlands, and sediment accumulates in embayments (**Fig. 15.11c**). In some cases, a headland erodes in stages (**Fig. 15.11d**). Because of refraction, waves curve and attack the sides of a headland, slowly eating through it to create a sea arch connected to the mainland by a narrow bridge. Eventually the arch collapses, leaving isolated **sea stacks** just offshore (Fig. 15.11d). Once formed, a sea stack protects the adjacent shore from waves. Therefore, sand may collect in the lee of the stack, slowly building a tombolo, a narrow ridge of sand that links the sea stack to the mainland.

Estuaries

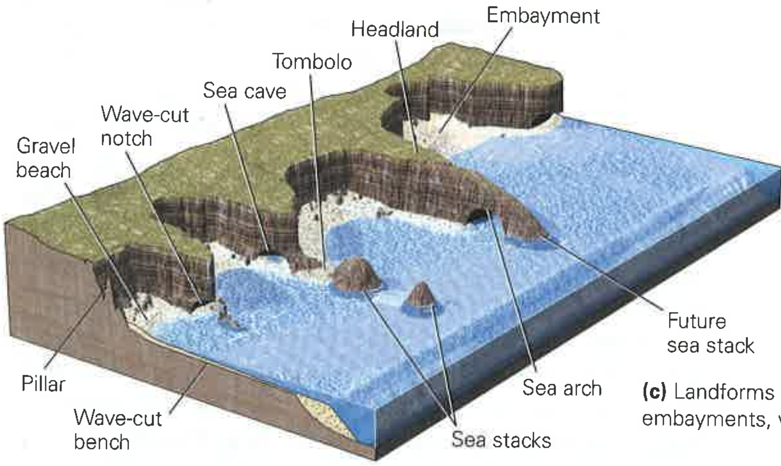
Along some coastlines, a relative rise in sea level causes the sea to flood river valleys that merge with the coast, resulting in **estuaries**, where seawater and river water mix. You can recognize an estuary on a map by the dendritic pattern of its river-carved coastline (**Fig. 15.12**). Oceanic and fluvial waters interact in two ways within an estuary. In quiet estuaries, protected from wave action or river turbulence, the water becomes stratified, with denser oceanic saltwater flowing upstream as a wedge beneath less-dense fluvial freshwater. In turbulent estuaries, oceanic and fluvial water combine to create nutrient-rich brackish water with a salinity between that of oceans and rivers. Estuaries are complex ecosystems inhabited by unique species of shrimp, clams, oysters, worms, and fish that can tolerate large changes in salinity.

FIGURE 15.11 Erosion landforms of rocky shorelines.



(a) A wave-cut notch.

(b) A wave-cut bench at the foot of the cliffs at Etretat, France.



(c) Landforms of a rocky shore. Beaches collect in embayments, whereas erosion concentrates at headlands.

(d) Coastal erosion along Australia's southern coast produced a sea arch (left). Eventually, the bridge will collapse, and only sea stacks will remain (right). These two are among several that together are known locally as the Twelve Apostles.

Fjords

During the last ice age, glaciers carved deep valleys in coastal mountain ranges. When the ice age came to a close, the glaciers melted away, leaving deep, U-shaped valleys (see Chapter 18). The water stored in the glaciers, along with the water within the vast ice sheets that covered continents during the ice age, flowed back into the sea and caused sea level to rise. The rising sea filled the deep valleys, creating **fjords**, or flooded glacial valleys. Coastal fjords are fingers of the sea surrounded by mountains; because of their deep-blue water and steep walls of polished rock, they are distinctively beautiful (**Fig. 15.13**).

Coastal Wetlands

A flat-lying coastal area that floods during high tide and drains during low tide, but does not get pummeled by intense waves, can host salt-resistant plants and evolve into a **coastal**

FIGURE 15.12 The Chesapeake Bay estuary formed when the sea flooded river valleys. The region is sinking relative to other coast areas because it overlies a buried meteor crater.

wetland. Wetland-dominated shorelines are sometimes called "organic coasts." Researchers distinguish among different types of coastal wetlands based on the plants they host. Examples include swamps (dominated by trees), marshes (dominated by grasses; **Fig. 15.14a**), and bogs (dominated by moss and shrubs). So many marine species spawn in wetlands that as a whole, wetlands account for 10% to 30% of marine organic productivity.

In tropical or semitropical climates (between 30° north and 30° south of the equator), mangrove trees may become the dominant plant in swamps (**Fig. 15.14b**). Some mangrove species form a broad network of roots above the water surface, making the plant look like an octopus standing on its tentacles, and some send up small protrusions from roots that rise above the water and allow the plant to breathe. Dense mangrove swamps counter the effects of stormy weather and thus prevent coastal erosion.

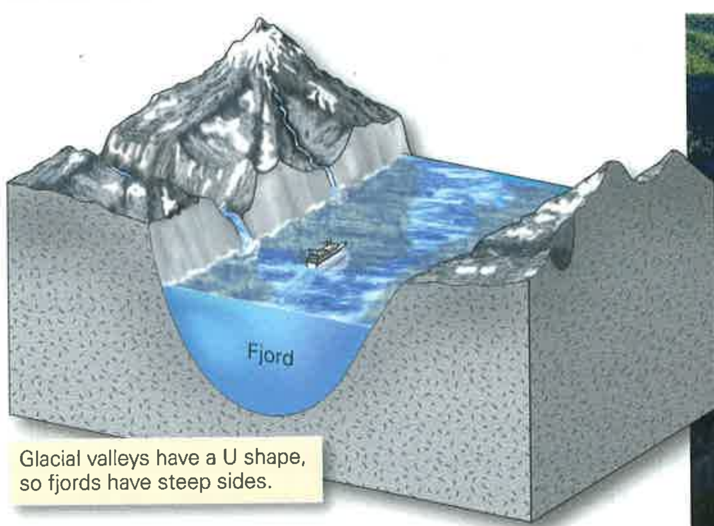
Coral Reefs

Along the azure coasts of Hawaii, visitors swim through colorful growths of living coral. Some corals look like brains, others like elk antlers, still others like delicate fans (**Fig. 15.15a**). Sea anemones, sponges, and clams grow on and around the coral. Though at first glance coral looks like a plant, it is actually a colony of tiny invertebrates related to jellyfish. An individual coral animal, or polyp, has a tube-like body with a head of tentacles.

Coral polyps secrete calcite shells, which gradually build into a mound of solid limestone whose top surface lies from just below the low-tide level down to a depth of about 60 m. At any given time, only the surface of the mound lives—the mound's interior consists of shells from previous generations of coral. The realm of shallow water underlain by coral mounds, associated organisms, and debris comprises a **coral reef**. Reefs absorb wave energy and thus serve as a living buffer zone that protects coasts from erosion. Corals need clear, well-lit, warm (18°–30°C) water with normal oceanic salinity, so coral reefs grow only along clean coasts at latitudes of less than about 30° (**Fig. 15.15b**).

Marine geologists distinguish three different kinds of coral reef, on the basis of their geometry (**Fig. 15.15c**). A fringing reef forms directly along the coast, a barrier reef develops offshore, and an atoll makes a circular ring surrounding a lagoon. As Charles Darwin first recognized back in 1859, coral reefs associated with islands in the Pacific start out as fringing reefs

FIGURE 15.13 Fjord landscapes form where relative sea-level rise drowns glacially carved valleys.



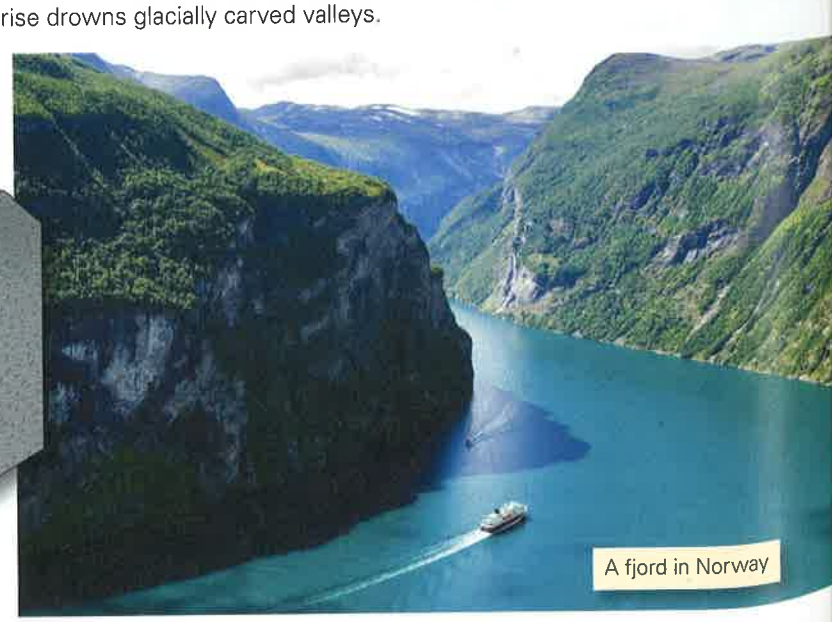


FIGURE 15.14 Examples of coastal wetlands.

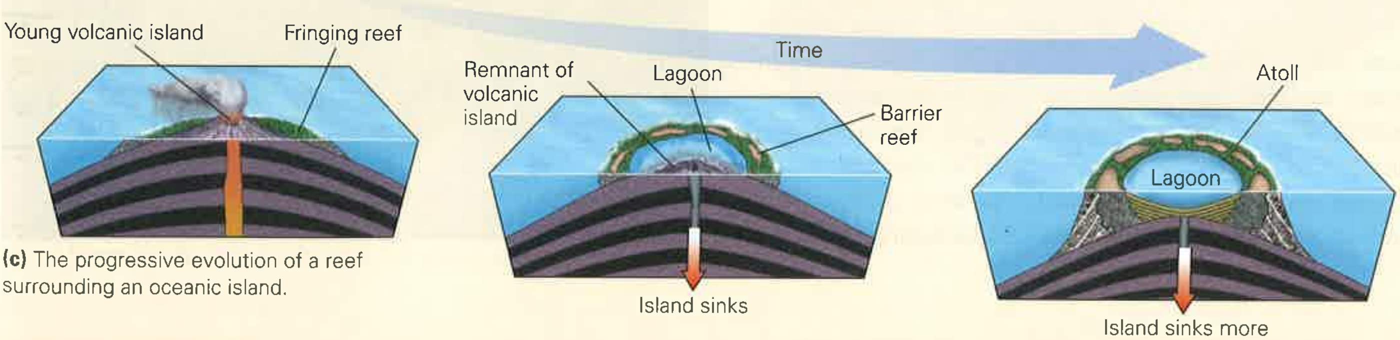
(a) A salt marsh along the coast of Cape Cod.

(b) A mangrove swamp in northeastern Brazil.

FIGURE 15.15 The character and evolution of coral reefs.

(a) The surface of this Hawaiian coral reef protects the shore from wave erosion. The underwater view emphasizes that a reef hosts a great variety of organisms.

(b) The distribution of warm-water coral reefs on Earth today.



(c) The progressive evolution of a reef surrounding an oceanic island.

and then later become barrier reefs and finally atolls. This progression reflects the continued growth of the reef as the island around which it formed gradually sinks. Eventually, the reef itself sinks too far below sea level to remain alive and becomes the cap of a flat-topped seamount known as a guyot.

Take-Home Message

Beaches form from wave-washed sediment; waves may build bars, and beach drift may produce spits. Rocky coasts evolve due to wave erosion, fjords are submerged glacial valleys, and estuaries are submerged river valleys. Some coasts host wetlands and reefs.

15.7 Causes of Coastal Variability

Plate Tectonic Setting

The tectonic setting of a coast plays a role in determining whether the coast has steep-sided mountain slopes or a broad plain that borders the sea (see **Geology at a Glance**, pp. 462–463). Along an active margin, compression squeezes the crust and pushes it up, creating mountains like the Andes along the western coast of South America. Along a passive margin, the cooling and sinking of the lithosphere may create a broad *coastal plain*, a flatland that merges with the continental shelf, as exists along the Gulf Coast and southeastern Atlantic coast of the United States.

Not all passive margins have coastal plains. The coastal areas of some passive margins were uplifted during the rifting event that preceded establishment of the passive margin. For example, highlands formed during rifting border the Red Sea and portions of the Brazilian and southern African coasts. Highlands also rise along the east coast of Australia.

Relative Sea-Level Changes

Sea level, relative to the land surface, changes during geologic time. Some changes develop due to vertical movement of the land. These may reflect plate-tectonic processes or the addition or removal of a load (such as a glacier) on the crust. Local changes in sea level may reflect human activity—when people pump out groundwater or oil, for example, the pores between grains in the sediment beneath the ground collapse, and the land surface sinks (see Chapter 16). Some relative sea-level changes, however, are due to a *global* rise or fall of the ocean surface. Such *eustatic sea-level changes* may reflect changes in the volume of mid-ocean ridges. An increase in the number or width of ridges, for example, displaces water and causes sea level to rise. Eustatic sea-level changes may also reflect changes in the volume of glaciers, for glaciers store water on land (**Fig. 15.16**). As glaciers grow, sea level falls, and as glaciers shrink, sea level rises.

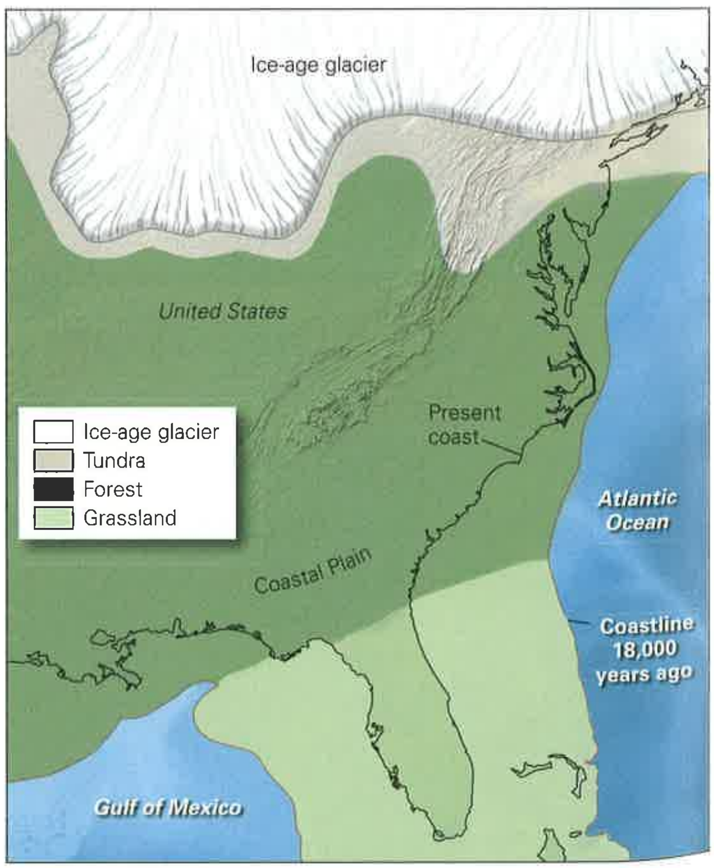
Geologists refer to coasts where the land is rising or rose relative to sea level as **emergent coasts**. At emergent coasts, steep slopes typically border the shore. A series of step-like terraces form along some emergent coasts (**Fig. 15.17a**). These terraces reflect episodic changes in relative sea level and/or ground uplift. Those coasts at which the land sinks relative to sea level become **submergent coasts** (**Fig. 15.17b**). At submergent coasts, landforms include estuaries and fjords that developed when the rising sea flooded coastal valleys.

Sediment Supply and Climate

The quantity and character of sediment supplied to a shore affects its character. That is, coastlines where the sea washes sediment away faster than it can be supplied (erosional coasts) recede landward and may become rocky, whereas coastlines that receive more sediment than erodes away (accretionary coasts) grow seaward and develop broad beaches.

Climate also affects the character of a coast. Shores that enjoy generally calm weather erode less rapidly than those constantly subjected to ravaging storms. A sediment supply large enough

FIGURE 15.16 Because of sea-level drop during the ice age, there was more dry land.



to generate an accretionary coast in a calm environment may be insufficient to prevent the development of an erosional coast in a stormy environment. The climate also affects biological activity along coasts. For example, in the warm water of tropical climates, mangrove swamps flourish along the shore, and coral reefs form offshore. The reefs may build into a broad carbonate platform such as appears in the Bahamas today. In cooler climates, salt marshes develop, whereas in arctic regions, the coast may be a stark environment of lichen-covered rock and barren sediment.

Take-Home Message

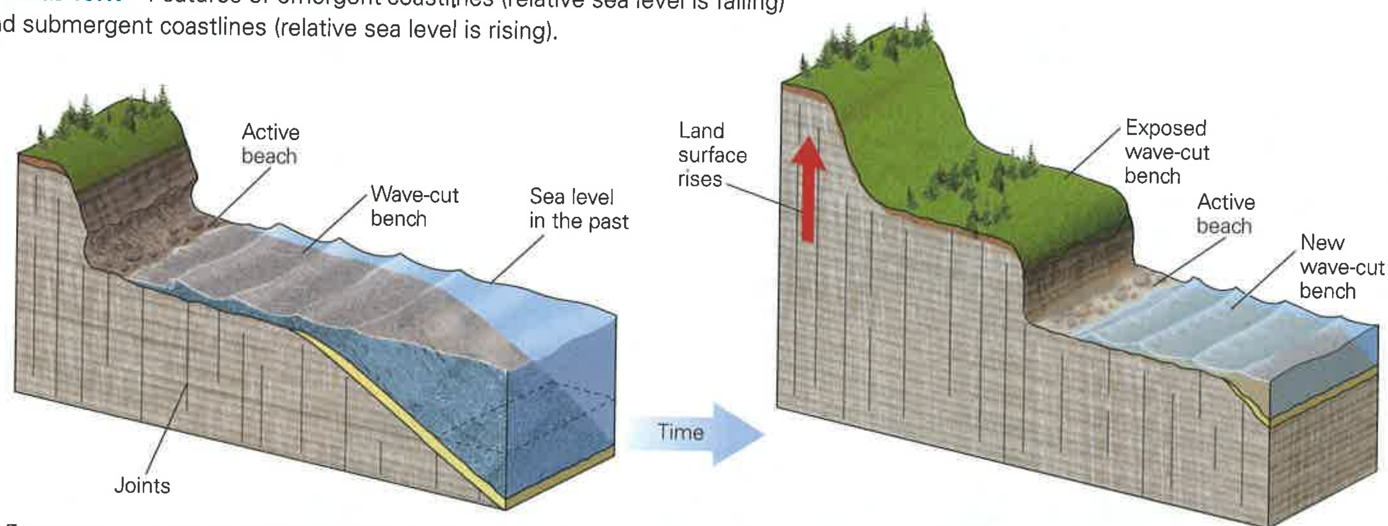
Tectonic activity and sediment supply influence the character of a coastline. At an emergent coast, land is rising relative to sea level, whereas at a submergent coast, it is sinking. Changing mid-ocean ridge and glacial volumes affect global sea level.

15.8 Coastal Problems and Solutions

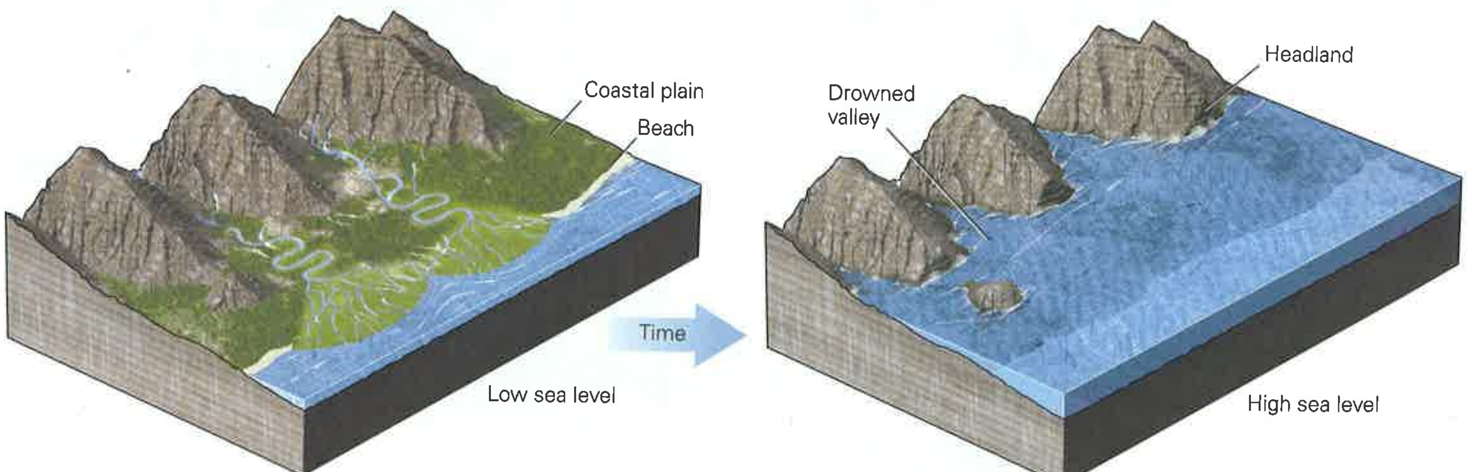
Contemporary Sea-Level Changes

People tend to view a shoreline as a permanent entity. But in fact, shorelines are ephemeral geologic features. On a time scale of hundreds to thousands of years, a shoreline moves inland or seaward depending on whether relative sea level rises or falls or whether sediment supply increases or decreases. In places where sea level is rising today, shoreline towns will eventually be submerged. For example, the Persian Gulf now covers about twice the area that it did 4,000 years ago. And if present rates of sea-level rise along the East Coast of the United States continue, major coastal cities such as Washington, New York, Miami, and Philadelphia may be inundated within the next millennium (**Fig. 15.18**).

FIGURE 15.17 Features of emergent coastlines (relative sea level is falling) and submergent coastlines (relative sea level is rising).



(a) *Emergent coasts*: Wave erosion produces a wave-cut bench along an emergent ooast. As the land rises, the bench becomes a terrace, and a new wave-cut bench forms.



(b) *Submergent coasts*: A coast before sea level rises. Rivers drain valleys and deposit sediment on a coastal plain. As a submergent coast forms, sea level rises and floods the valleys, and waves erode the headlands.

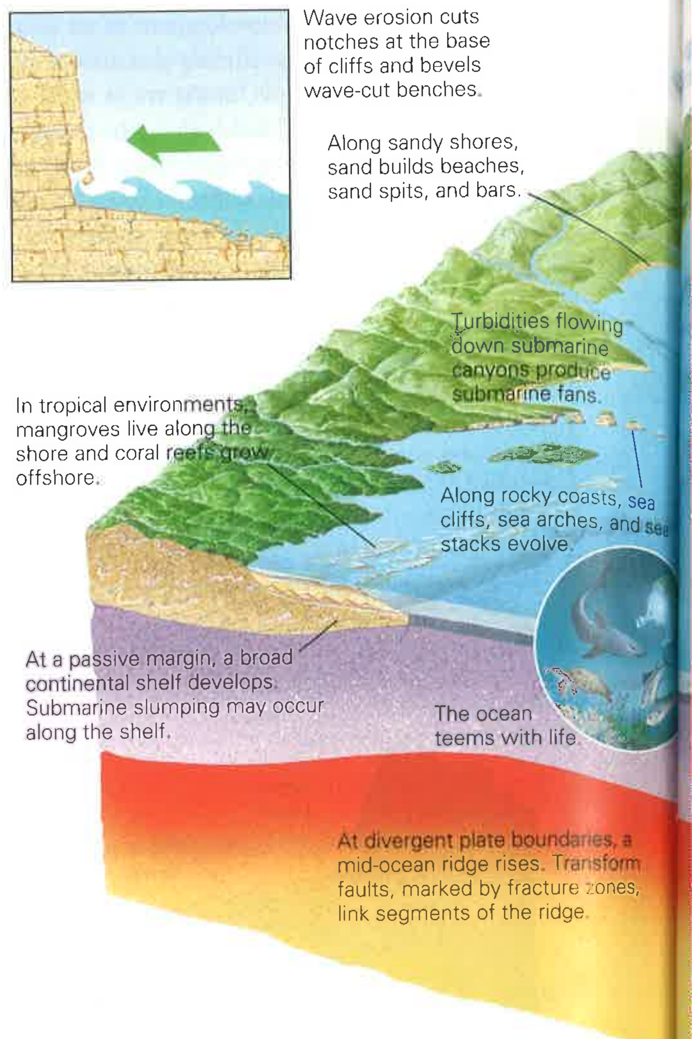
Oceans and Coasts

The oceans of the world host a diverse array of environments and landscapes, illustrating the complexity of the Earth System. Tectonic processes and surface processes working alone or in tandem generate unique features beneath the sea and along its coasts.

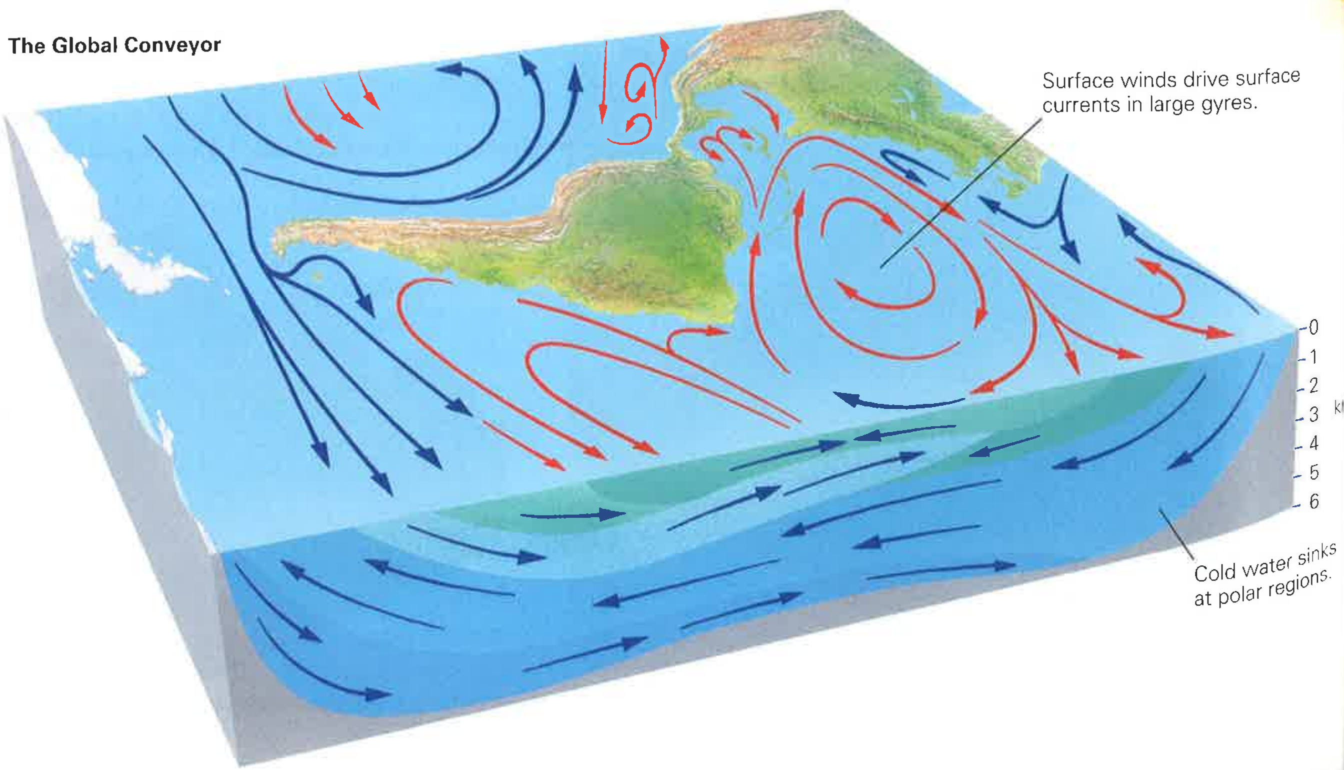
The major structures of the ocean floor are the result of plate-tectonic activity. For example, mid-ocean ridges define divergent boundaries, fracture zones form along transform faults, and trenches mark subduction zones. Oceanic islands, seamounts, and plateaus build above hot spots. Along passive continental margins, broad continental shelves develop, locally incised by submarine canyons, as sediment buries stretched continental lithosphere. Along convergent margins, accretionary prisms and volcanic arcs grow.

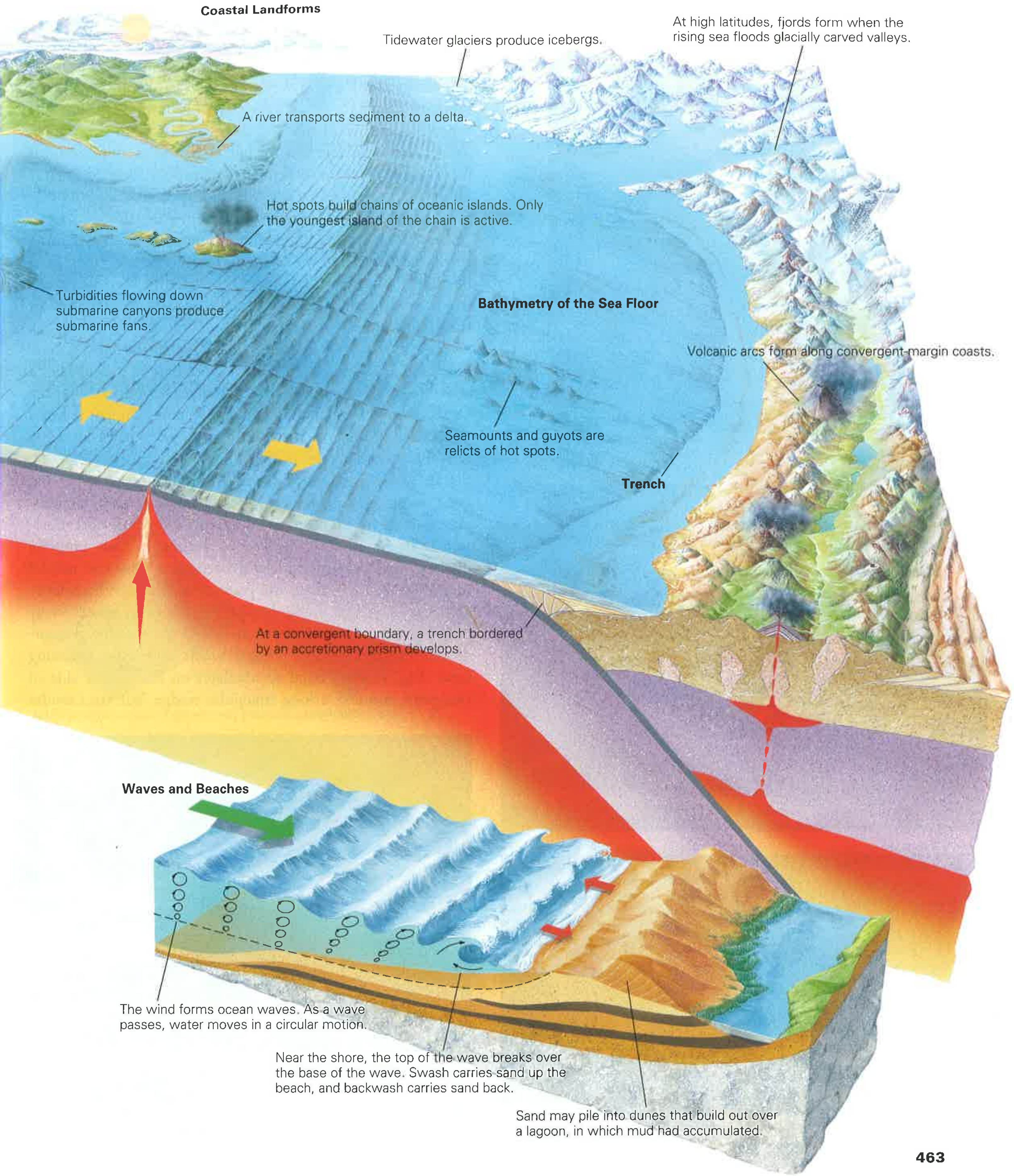
Within the ocean, currents circulate water due to regional variations in both water salinity and temperature (factors that control density) and to the traction between wind and the water surface. Tides cause sea level to rise and fall, and wind builds waves that churn the sea surface, erode shorelines, and transport sediment.

Coastal landscapes reflect variations in sediment supply, relative sea-level rise or fall, and climate. For example, where the supply of sediment is low and the landscape is rising relative to sea level, rocky shores with dramatic cliffs and sea stacks may evolve. Where sediment is abundant, sandy beaches and bars develop. Regions where glaciers carved deep valleys now feature spectacular fjords. Protected coastal areas, especially those in warm climates, host unique coastal ecosystems inhabited by grasses, mangroves, and/or corals. Corals may contribute to growth of broad reefs along the shore. Human activities can significantly affect coastal landscape.



The Global Conveyor





Coastal Landforms
Tidewater glaciers produce icebergs.
At high latitudes, fjords form when the rising sea floods glacially carved valleys.
A river transports sediment to a delta.
Hot spots build chains of oceanic islands. Only the youngest island of the chain is active.
Turbidities flowing down submarine canyons produce submarine fans.
Bathymetry of the Sea Floor
Volcanic arcs form along convergent-margin coasts.
Seamounts and guyots are relicts of hot spots.
Trench
At a convergent boundary, a trench bordered by an accretionary prism develops.
Waves and Beaches
The wind forms ocean waves. As a wave passes, water moves in a circular motion.
Near the shore, the top of the wave breaks over the base of the wave. Swash carries sand up the beach, and backwash carries sand back.
Sand may pile into dunes that build out over a lagoon, in which mud had accumulated.

FIGURE 15.18 Future sea-level rise, due to melting of polar ice, would flood many coastal cities.

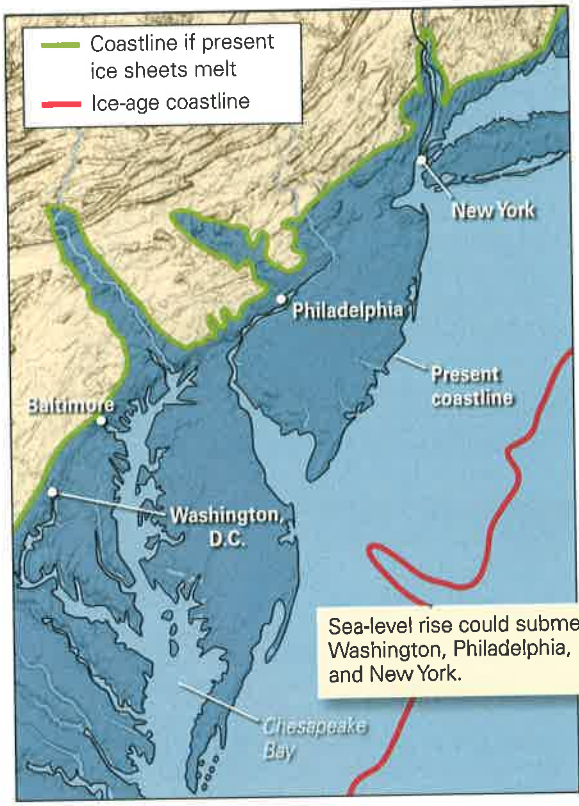


FIGURE 15.19 Examples of beach erosion.

(a) When Hurricane Ike hit Galveston, Texas, in September 2008, many beachfront homes were washed away.

(b) Wave erosion has completely removed the beach, and has started to erode a beach cliff, along the coast of Cape Cod.

Beach Destruction—Beach Protection?

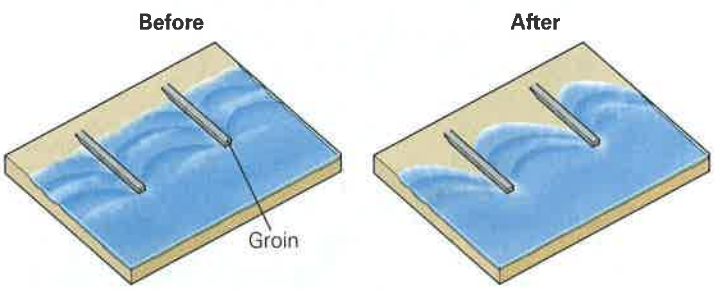
In a matter of hours, a storm—especially a hurricane—can radically alter a landscape that took centuries or millennia to form. The backwash of storm waves sweeps vast quantities of sand seaward, leaving the beach a skeleton of its former self. The surf submerges barrier islands and shifts them toward the lagoon. Waves and wind together rip out mangrove swamps and salt marshes and break up coral reefs, thereby destroying the organic buffer that can protect a coast, leaving it vulnerable to erosion for years to come. Of course, major storms also destroy human constructions: erosion undermines shoreside buildings, causing them to collapse into the sea; wave impacts smash buildings to bits; and the storm surge—very high water levels created when storm winds push water toward the shore—floats buildings off their foundations (Fig. 15.19a, b).

But even less-dramatic events, such as the loss of river sediment, a gradual rise in sea level, a change in the shape of a shoreline, or the destruction of coastal vegetation, can alter the balance between sediment accumulation and sediment removal on a beach, leading to beach erosion. In some places, beaches retreat landward at rates of 1 to 2 m per year.

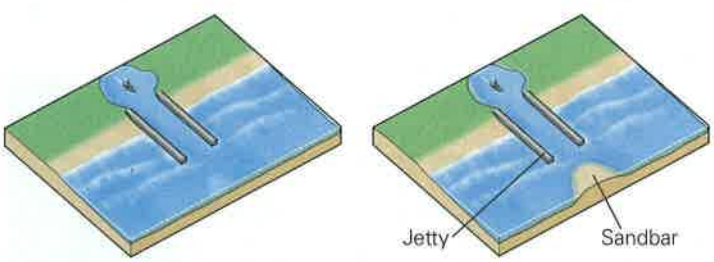
In many parts of the world, beachfront property has great value; but if a hotel loses its beach sand, it probably won't stay in business. Similarly, a harbor can't function if its mouth gets blocked by sediment. Thus property owners often construct artificial barriers to alter the natural movement of sand along the coast, sometimes with undesirable results. For example, beach-front property owners may build groins, concrete or stone walls protruding perpendicular to the shore, to prevent beach drift from removing sand (Fig. 15.20a). Sand accumulates on the updrift side of the groin, forming a long triangular wedge, but sand erodes away on the downdrift side. Needless to say, the property owner on the downdrift side doesn't appreciate this process. Harbor engineers may build a pair of walls called jetties to protect the entrance to a harbor (**Fig. 15.20b**). But jetties erected at the mouth of a river channel effectively extend the river into deeper water and thus may lead to the deposition of an offshore sandbar. Engineers may also build an offshore wall called a breakwater, parallel or at an angle to the beach, to prevent the full force of waves from reaching a harbor. With time, however, sand builds up in the lee of the breakwater and the beach grows seaward, clogging the harbor (**Fig. 15.20c**). To protect expensive shoreside construction, people build seawalls out of riprap (large stone or concrete blocks) or reinforced concrete on the landward side of the beach (**Fig. 15.20d**), but during a storm, these can be undermined.

In some places, people have given up trying to decrease the rate of beach erosion and instead have worked to increase the rate of sediment supply. To do this, they pump sand from farther offshore, or truck in sand from elsewhere to replenish a beach. This procedure, called beach nourishment, can be hugely expensive and at best provides only a temporary fix, for the backwash and beach drift that removed the sand in the first place continue unabated as long as the wind blows and the waves break.

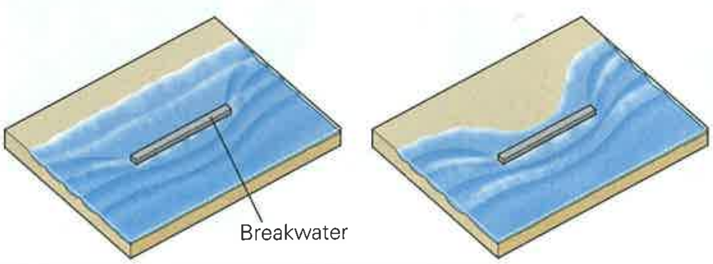
FIGURE 15.20 Techniques used to preserve beaches.



(a) The construction of groins may produce a sawtooth beach.



(b) Jetties extend a river farther into the sea, but may cause a sandbar to form at the end of the channel.



(c) A beach may grow seaward behind a breakwater.

(d) Riprap will slow erosion of a parking lot along a California beach.

Destruction of Wetlands and Reefs

Bad cases of beach pollution create headlines. Because of beach drift, garbage dumped in the sea in an urban area may drift along the shore and be deposited on a tourist beach far from its point of introduction. Oil spills, from ships that flush their bilges or from tankers that have run aground or foundered in stormy seas, or from offshore well leaks, have contaminated shorelines at several places around the world.

The influx of nutrients, from sewage and agricultural runoff, into coastal waters can create dead zones along coasts. A *dead zone* is a region in which water contains so little oxygen that fish and other organisms within it die. Dead zones form when the concentration of nutrients rises enough to stimulate an algae bloom, for overnight respiration by algae depletes dissolved oxygen in the water, and the eventual death and decay of plankton depletes oxygen even more. One of the world's largest dead zones occurs in the Gulf of Mexico, offshore of the Mississippi River's mouth.

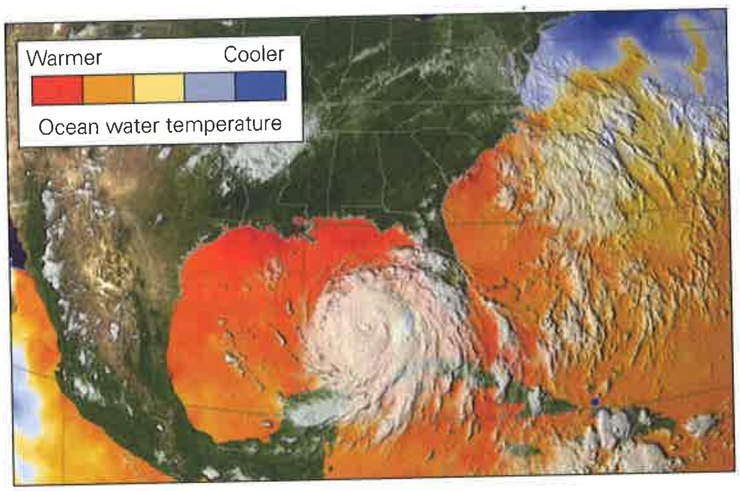
Coastal wetlands and coral reefs are particularly susceptible to changes in the environment, and many of them have been destroyed in recent decades. Their loss both increases a coast's vulnerability to erosion and, because they provide spawning grounds for marine organisms, disrupts the global food chain. Destruction of wetlands and reefs happens for many reasons. Wetlands have been filled or drained to be converted to farmland, housing developments, resorts, or garbage dumps. Reefs have been destroyed by boat anchors, dredging, the activities of divers, dynamite explosions intended to kill fish, and quarrying operations intended to obtain construction materials. Chemicals and particulates entering coastal water from urban, industrial, and agricultural areas can cause havoc in wetlands and reefs, for these materials cloud water and/or trigger algal blooms, killing filter-feeding organisms. Toxic chemicals in such runoff can also poison plankton and burrowing organisms and, therefore, other organisms progressively up the food chain.

Global climate change also impacts the health of organic coasts (see Chapter 19). For example, transformation of once vegetated regions into deserts means that the amount of dust carried by winds from the land to the sea has increased. This dust can interfere with coral respiration and can bring dangerous viruses. A global increase in seawater temperature may be contributing to *reef bleaching*, the loss of coral color due to the death of the algae that live in coral polyps. The statistics of wetland and reef destruction worldwide are frightening—ecologists estimate that between 20% and 70% of wetlands have already been destroyed, and along some coasts, 90% of reefs have died.

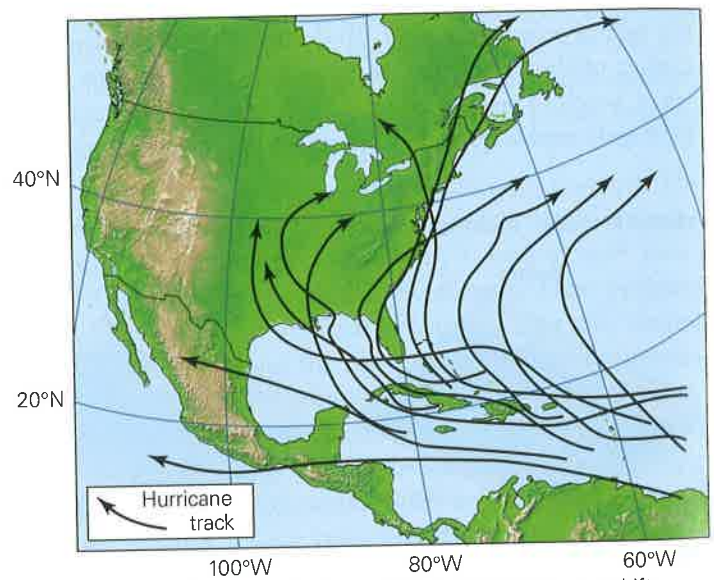
Hurricanes—A Coastal Calamity

Global-scale convection of the atmosphere, influenced by the Coriolis effect, causes currents of warm air to flow steadily from east to west in tropical latitudes. As the air flows over the ocean, it absorbs moisture. Because air becomes less dense as it gets warmer, tropical air eventually begins to rise like a balloon. As the air rises, it cools, and the water vapor it contains condenses to form clouds (mists of very tiny water droplets). If the air contains sufficient moisture, the clouds grow into a cluster of large thunderstorms, which consolidate to form a single, very large storm. Because of the Coriolis effect, this large storm evolves into a rotating swirl called a tropical disturbance. If the disturbance remains over warm ocean water, as can happen in late summer and early fall, rising warm moist air

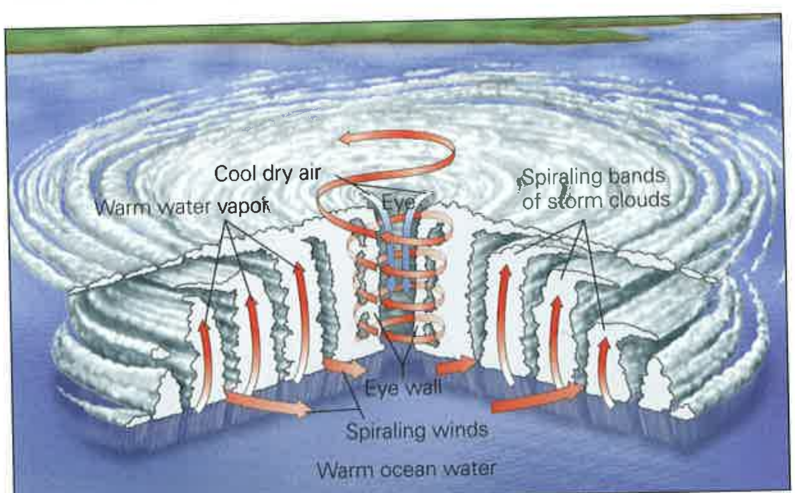
FIGURE 15.21 Characteristics and paths of hurricanes in the western North Atlantic.



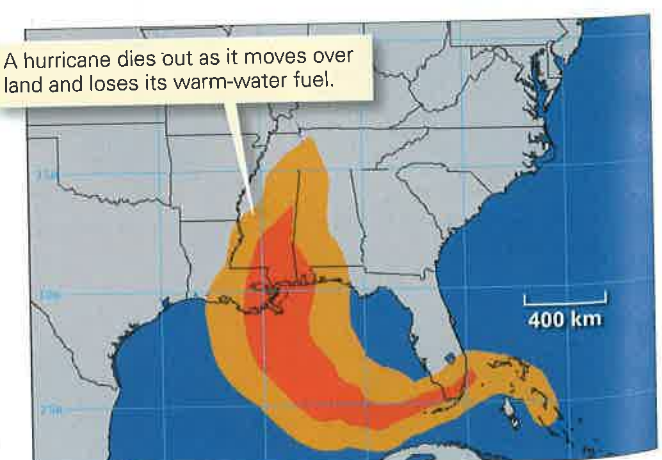
(a) A 2005 satellite photograph of Hurricane Katrina entering the Gulf of Mexico, where very warm waters fed the storm.



(b) Tracks of several Atlantic hurricanes show how most drift westward, then northward.



(c) In this cutaway drawing, we can see the spirals of clouds, the eye, and the eye wall of a hurricane. Dry air descends in the eye.



(d) A wind-swath map of Hurricane Katrina. Red areas represent hurricane winds; orange areas represent tropical-storm winds.

continues to feed the storm, fostering more growth. Eventually a spiral of rapidly circulating clouds forms, and the tropical disturbance becomes a tropical depression. Additional nourishment causes the tropical depression to spin even faster and grow broader, until it becomes a tropical storm and receives a name. If a tropical storm becomes powerful enough, it becomes a tropical cyclone. Formally defined, a *tropical cyclone* is a huge rotating storm, which forms in tropical latitudes, and in which winds exceed 119 km per hour (74 mph). It resembles a giant counterclockwise spiral of clouds—300 to 1,500 km (930 miles) wide—when viewed from space (**Fig. 15.21a**). Such a storm is called a **hurricane** in the Atlantic and eastern Pacific, a typhoon in the western Pacific, and simply a cyclone around Australia and in the Indian Ocean.

Atlantic hurricanes generally form in the ocean to the east of the Caribbean Sea, though some form in the Caribbean itself. They first drift westward at speeds of up to 60 km per hour (37 mph). They may eventually turn north and head into the North Atlantic or into the interior of North America, where they die when they run out of a supply of warm water (**Fig. 15.21b**). Weather researchers classify the strength of hurricanes using the Saffir-Simpson scale, which runs from 1 to 5; somewhat different scales are used for typhoons and cyclones. On the Saffir-Simpson scale, a Category 5 hurricane has sustained winds of $\geq$250 km/hr ($\geq$156 mph). The highest wind speed ever recorded during a hurricane was in excess of 300 km/hr.

A typical hurricane (or typhoon or cyclone) consists of several spiral arms extending inward to a central zone of relative calm known as the hurricane's *eye* (**Fig. 15.21c**). A rotating vertical cylinder of clouds, the eye wall, surrounds the eye. Winds spiral toward the eye, so like an ice skater who spins faster when she brings her arms inward, the winds accelerate toward the interior of the storm and are fastest along the eye wall. Thus, hurricane-force winds affect a belt that is only 15% to 35% as wide as the whole storm (**Fig. 15.21d**). On the side of the eye where winds blow in the same direction as the whole storm is moving, the ground speed of winds is greatest, because the storm's overall speed adds to the rotational motion.

Hurricanes pose extreme danger in the open ocean, because their winds cause huge waves to build, and thus have led to the foundering of countless ships. They also cause havoc in coastal regions, and even inland, though they die out rapidly after moving onshore. The coastal damage happens for several reasons:

- *Wind*: Winds of weaker hurricanes tear off branches and smash windows. Stronger hurricanes uproot trees, rip off roofs, and collapse walls.
- *Waves*: Winds shearing across the sea surface during a hurricane generate huge waves. In the open ocean, these waves can capsize ships. Near shore, waves batter and erode beaches, rip boats from moorings, and destroy coastal property.
- *Storm surge*: Rising air in a hurricane causes a region of extremely low air pressure beneath. This decrease in pressure causes the surface of the sea to bulge upward over an area with a diameter of 60 to 80 km. Sustained winds blowing in an onshore direction build this bulge even higher. When the hurricane reaches the coast, the bulge of water, or storm surge, swamps the land. If the bulge hits the land at high tide, the sea surface will be especially high and will affect a broader area.
- *Rain, stream flooding, and landslides*: Rain drenches the Earth's surface beneath a hurricane. In places, half a meter or more of rain falls in a single day. Rain causes streams to flood, even far inland, and can trigger landslides.
- *Disruption of social structure*: When the storm passes, the hazard is not over. By disrupting transportation and communication networks, breaking water mains, and washing away sewage-treatment plants, hurricane damage creates severe obstacles to search and rescue, and can lead to the spread of disease, fire, and looting.

Nearly all hurricanes that reach the coast cause death and destruction, but some are truly catastrophic. Storm surge from a 1970 cyclone making landfall on the low-lying delta lands of Bangladesh led to an estimated 500,000 deaths. In 1992, Hurricane Andrew leveled extensive areas of southern Florida, causing over $30 billion in damage and leaving 250,000 people homeless. Hurricane Katrina, in 2005, stands as the most destructive hurricane to strike the United States. Let's look at this storm's history.

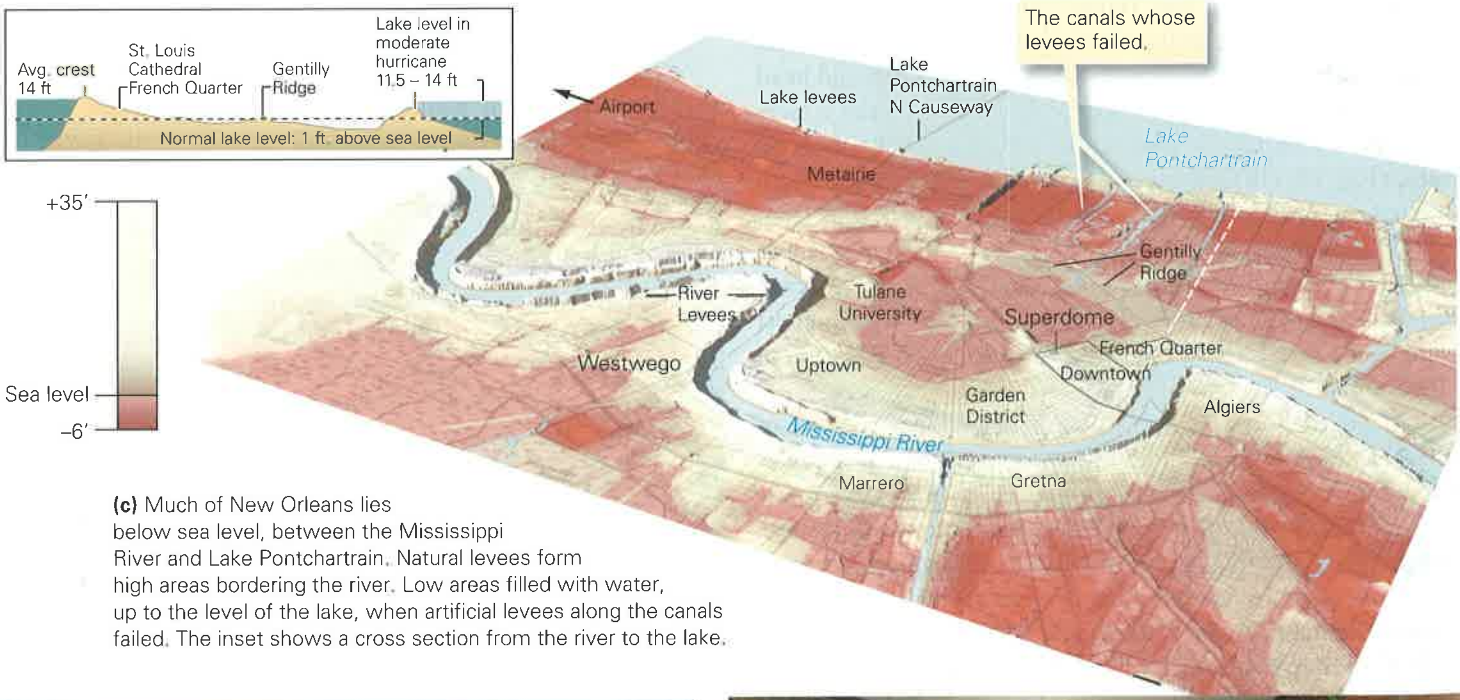
Hurricane Katrina

Tropical Storm Katrina came into existence over the Bahamas and headed west. Just before landfall in southeastern Florida, winds strengthened and the storm became Hurricane Katrina. This hurricane sliced across the southern tip of Florida, causing several deaths and millions of dollars in damage. It then entered the Gulf of Mexico and passed directly over the Loop Current, an eddy of summer-heated water from the Caribbean that had entered the Gulf of Mexico. Water in the Loop Current reaches temperatures of 32°C (90°F), and thus stoked the storm, injecting it with a burst of energy sufficient for the storm to morph into a Category 5 monster whose swath of hurricane-force winds reached a width of 325 km (200 miles). When it entered the central Gulf of Mexico, Katrina turned north and began to bear down on the Louisiana-Mississippi coast. The eye of the storm passed just east of New Orleans, and then across the coast of Mississippi. Storm surges broke records, in places rising 7.5 m (25 feet) above sea level, and they washed coastal communities off the

FIGURE 15.22 The devastation of coastal areas by Hurricane Katrina.

(a) Surge from the storm destroyed homes along the Alabama coast.

(b) Officials survey the storm damage.



(c) Much of New Orleans lies below sea level, between the Mississippi River and Lake Pontchartrain. Natural levees form high areas bordering the river. Low areas filled with water, up to the level of the lake, when artificial levees along the canals failed. The inset shows a cross section from the river to the lake.

(d) Water flowing across the levees bordering the 17th Street Canal after the hurricane had passed.

(e) The flooded interior of a New Orleans home.

map along a broad swath of the Gulf Coast (**Fig. 15.22a, b**). In addition to the devastating wind and surge damage, Katrina led to the drowning of New Orleans.

To understand what happened to New Orleans, we must consider the city's geologic history. New Orleans grew on the Mississippi Delta, between the banks of the Mississippi River on the south and Lake Pontchartrain (actually a bay of the Gulf of Mexico) on the north. The older parts of the town grew up on the relatively high land of the Mississippi's natural levee. Younger parts of the city, however, spread out over the topographically lower delta plain. As decades passed, people modified the surrounding delta landscape by draining wetlands, by constructing artificial levees that confined the Mississippi River, and by extracting groundwater. Sediment beneath the delta compacted, and the delta's surface has been starved of new sediment, so large areas of the delta sank below sea level. Today, most of New Orleans lies in a bowl-shaped depression as much as 2 m (7 feet) below sea level—the hazard implicit in this situation had been recognized for years (**Fig. 15.22c**).

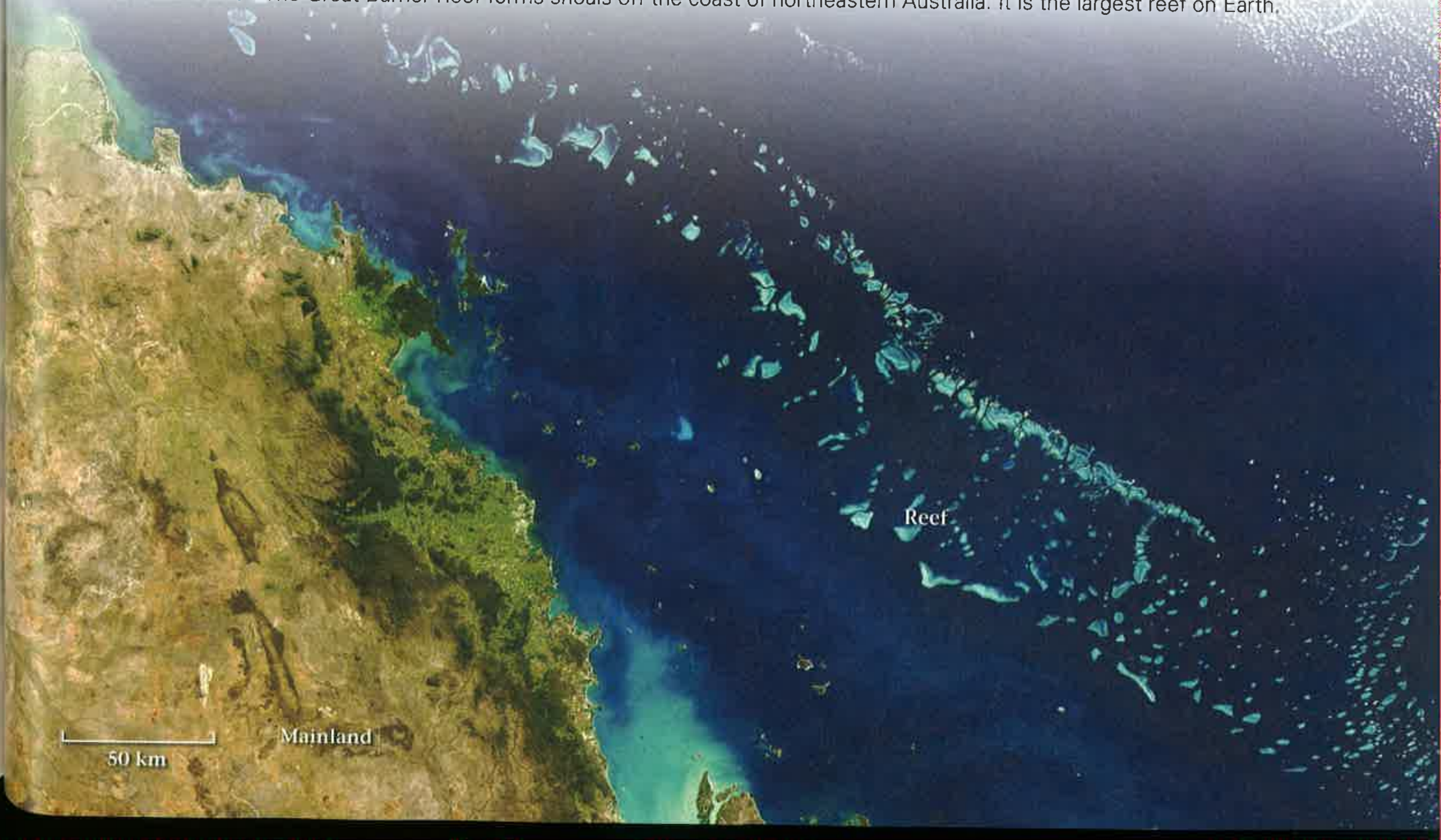
The winds of Hurricane Katrina ripped off roofs, toppled trees, smashed windows, and triggered the collapse of weaker buildings, but their direct consequences were not catastrophic. However, when the winds blew storm surge into Lake Pontchartrain, its water level rose beyond most expectations and pressed against the system of artificial levees and flood walls that had been built to protect New Orleans. Hours after the hurricane eye had passed, the high water of Lake Pontchartrain found a weakness along the floodwall bordering a drainage canal and pushed out a section. Breaks eventually formed in a few other locations as well. So, a day after the hurricane was over, New Orleans began to flood. As the water line climbed the walls of houses, brick by brick, residents fled first upstairs, then to their attics, and finally to their roofs. Water spread across the city until the bowl of New Orleans filled to the same level as Lake Pontchartrain, submerging 80% of the city (**Fig. 15.22d**)

Floodwaters washed some houses away and filled others with debris (**Fig. 15.22e**). The disaster took on national significance, as the trapped population sweltered without food, drinking water, or adequate shelter. With no communications, no hospitals, and few police, the city almost descended into anarchy. It took days for outside relief to reach the city, and by then, many had died and parts of New Orleans, a cultural landmark and major port, had become uninhabitable.

Take-Home Message

Coastal landscapes can be impacted by human activities or climate change. Beaches and bars erode, pollution destroys wetlands, and hurricanes ravage the landscape. People try to protect beaches by constructing barriers or replenishing sand, but this can lead to other problems.

ANOTHER VIEW The Great Barrier Reef forms shoals off the coast of northeastern Australia. It is the largest reef on Earth.



Chapter Summary

- The landscape of the sea floor depends on the character of the underlying crust. Wide continental shelves form over passive-margin basins. Continental shelves are cut by submarine canyons. Abyssal plains develop on old, cool oceanic lithosphere. Seamounts form above hot spots.
- The salinity, temperature, and density of seawater vary with location and depth.
- Water in the oceans circulates in currents. Surface currents are driven by the wind and are deflected by the Coriolis effect. The vertical upwelling and downwelling of water create deep currents. Some of this movement is thermohaline circulation.
- Tides—the daily rise and fall of sea level—are caused by a tide-generating force. The largest contribution to this force comes from the gravitational pull of the Moon.
- Waves are caused by friction where the wind shears across the surface of the ocean. Water particles follow a circular motion in a vertical plane as a wave passes. Waves refract (bend) when they approach the shore because of frictional drag with the sea floor.
- Sand on beaches moves with the swash and backwash of waves. If there is a longshore current, the sand gradually moves along the beach and may build spits.
- At rocky coasts, waves grind away at rocks, yielding such features as wave-cut benches and sea stacks. Some shores are wetlands, where marshes or mangrove swamps grow. Coral reefs grow along coasts in warm, clear water.
- The differences in coasts reflect their tectonic setting, whether sea level is rising or falling, sediment supply, and climate.
- To protect beach property, people build groins, jetties, breakwaters, and seawalls.
- Human activities have led to the pollution of coasts. Reef bleaching has become dangerously widespread.
- Hurricanes produce winds of between 119 and 300 km per hour. The force of the winds, along with storm surge and heavy rains, can destroy coastal areas.

Key Terms

abyssal plain (p. 446)
backwash (p. 453)
barrier island (p. 456)
bathymetry (p. 446)
beach (p. 454)
coast (pp. 445, 454)
coastal wetland (p. 457–458)
continental shelf (p. 446)
coral reef (p. 458)
Coriolis effect (p. 449)
current (p. 449)
emergent coast (p. 460)
estuary (p. 456)
fjord (p. 457)
gyre (p. 450)
hurricane (p. 467)
lagoon (p. 456)
longshore current (p. 453)
longshore drift (p. 453)
offshore bar (p. 456)
rogue wave (p. 453)
salinity (p. 449)
sand spit (p. 456)
seamount (p. 448)
sea stack (p. 456)
submarine canyon (p. 447)
submergent coast (p. 460)
swash (p. 453)
thermocline (p. 449)
thermohaline circulation (p. 451)
tidal reach (p. 451)
tide (p. 451)
wave base (p. 452)
wave-cut bench (p. 456)
wave-cut notch (p. 456)
wave refraction (p. 453)

Review Questions

1. How much of the Earth's surface is covered by oceans? What proportion of the world's population lives near a coast?
2. How does the lithosphere beneath a passive margin differ from that beneath an abyssal plain?
3. How do the shelf and slope of an *active* continental margin differ from those of a *passive* margin?
4. Where does the salt in the ocean come from? How do the salinity and temperature in the ocean vary?
5. What factors control the direction of surface currents in the ocean? What is the Coriolis effect, and how does it affect oceanic circulation? Explain thermohaline circulation.
6. What causes the tides? Why do the range and reach of tides vary with location?
7. Describe the motion of water molecules in a wave. How does wave refraction cause longshore currents?
8. Describe the components of a beach profile. How does beach sand migrate as a result of longshore currents?
9. Describe how rocky coasts evolve.
10. What is an estuary? Why is it such a delicate ecosystem? What is the difference between an estuary and a fjord?
11. Discuss the different types of coastal wetlands. Describe the different kinds of reefs, and how a reef surrounding an oceanic island changes with time.

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Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- An animation-based exercise on longshore drift.
- A video-based exercise showing sea surface currents and temperature.
- A What a Geologist Sees exercise that helps students calculate wave base depth.

12. How do plate tectonics, sea-level changes, sediment supply, and climate change affect the shape of a coastline? Explain the difference between emergent and submergent coasts.
13. In what ways do people try to modify or "stabilize" coasts? How do the actions of people threaten coastal areas?
14. Where do hurricanes form, and how can they affect coasts?

On Further Thought

15. In 1789, the crew of the HMS *Bounty* mutinied. Near Tonga, in the Friendly Islands (approximately 20°S and 175°W), the crew forced the ship's commanding officer, Lieutenant Bligh, along with those crewmen who remained loyal to Bligh, into a rowboat and set them adrift in the Pacific Ocean. The castaways, amazingly, survived; 47 days later, they landed at Timor (near Sumatra), 6,700 km to the west. Why did they end up where they did?

SEE FOR YOURSELF O. . . Oceans and Coastlines

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet O of our **Geotours Workbook**.

Coral Reefs, Pacific

Latitude 16°47′26.92″S,
Longitude 150°58′1.27″W

From 20 km, you can see the fringing reef of Huahine. Waves break on the outer edge of the reef, coral buildups lie beneath the surface, and sand partially fills the lagoon. The island itself represents the subsiding remnants of a hot-spot volcano.

Groins of Chicago's shore

Latitude 41°54′59.76″N,
Longitude 87°37′36.41″W

From 2 km elevation, you see the sandy beaches that fringe the coastline of Lake Michigan. Waves strike the shore obliquely. As a result, beach drift carries sand southwards. The city constructed a series of groins, in an attempt to prevent beach erosion.

Organic Coast, Florida

Latitude 28°8′51.24″N,
Longitude 80°42′32.53″W

Along Florida's southern coast, thickets of mangroves (viewed from 8 km) line the shore and separate swamps from the sea. The roots of these trees protect the coast from wave erosion.

Fjords of Norway

Latitude 60°53′56.09″N,
Longitude 5°12′31.84″E

During the last ice age, glaciers carved deep, steep-sided valleys into the mountains of western Norway. When the glaciers melted and sea level rose, the valleys filled with water, forming the fjords we can now see from 80 km.