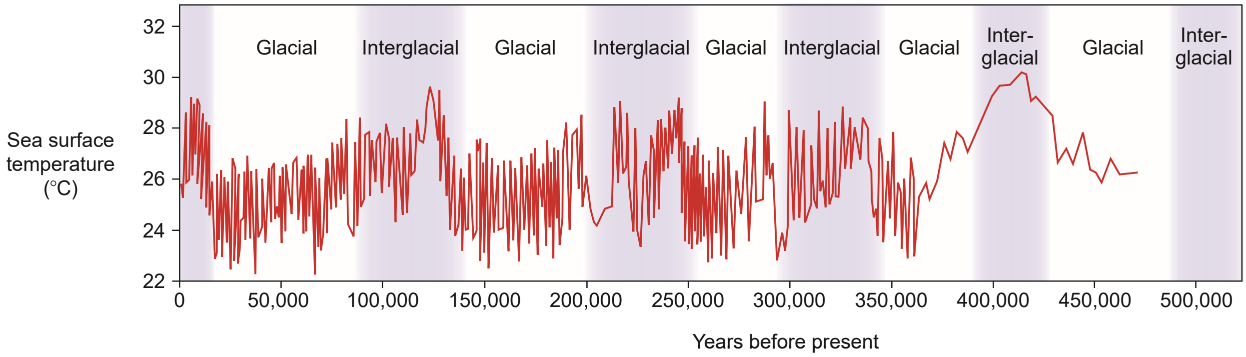


FIGURE 2.18 A history of the earth's climate over the past half-million years as determined from foraminiferan microfossils. The red line shows the average sea surface temperature in the equatorial Pacific Ocean as determined from the magnesium-to-calcium ratio in the microfossils. The white and blue bands indicate major glacial and interglacial periods, respectively, recorded in oxygen isotope ratios. Note that the shifts between ice ages and interglacial periods involve relatively small changes in average temperature.

used to determine the age of microfossils. It is also possible to tell the temperature of the water in which the organisms lived by measuring the ratios of magnesium (Mg) to calcium (Ca) or of different isotopes of oxygen in the microfossils. Thus, microfossils have preserved a detailed record of the earth's past climate. Though the record in the sediments is not always easy to read, it is supplemented by other information. The ratio of the elements strontium (Sr) and calcium in ancient coral skeletons, for example, also records past ocean temperatures. Ice cores from polar areas like Greenland and Antartica also preserve a record of past temperatures, as well as samples of the ancient atmosphere in the form of tiny bubbles trapped in the ice. These and other studies are providing an increasingly detailed picture of the earth's past climate (see "Rolling the Dice: Climate Change," p. 231).

Climate and Changes in Sea Level The climate of the earth has fluctuated rhythmically through much of its history, alternating between warm, or **interglacial,** periods and cold periods, or **ice ages** (Fig. 2.18). The earth is presently in an interglacial period. During ice ages, great glaciers build up on the continents. Because large amounts of water are trapped as ice instead of flowing to the sea in rivers, there is less water in the ocean. Thus, sea level falls during ice ages.

The **Pleistocene Epoch,** which began a little less than 2 million years ago, was the last major period of glaciation. During the Pleistocene a series of ice ages was interspersed by brief warm periods of melting. The peak of the last ice age occurred about 18,000 years ago. At that time, vast ice sheets as thick as 3 km (2 mi) covered much of North America and Europe. Sea level was about 130 m (425 ft) lower than it is today.

Sea level falls during ice ages because water is trapped in glaciers on the continents. The last major ice age occurred about 18,000 years ago.

Sea level continues to rise, though the rate of melting slowed during the past 3,000 years. Some scientists think that without the influence of humans the earth would be entering another ice age. Human impact on the atmosphere, however, has intensified the **greenhouse effect.** Global temperatures and the rate of glacial melting are now increasing, and sea level is projected to continue to rise for at least the next century (see "Special Report: Our Changing Planet," p. 231).

THE GEOLOGICAL PROVINCES OF THE OCEAN

The structure of the ocean floor is dominated by the workings of plate tectonics. Because this is a global process, the major features of the sea floor are quite similar from place to place around the world. The sea floor is divided into two main regions: the **continental margins,** which represent the submerged edges of the continents, and the deep-sea floor itself.

Continental Margins

The continental margins are the boundaries between continental crust and oceanic crust. Most of the sediment from the continents settles to the bottom soon after reaching the sea and accumulates on the continental margins. Sediment deposits on the continental margins may be as thick as 10 km (6 mi). Continental margins generally consist of a shallow, gently sloping **continental shelf,** a steeper **continental slope** seaward of the continental shelf, and another gently sloping region, the **continental rise,** at the base of the continental slope (Fig. 2.19).

Diatoms Single-celled algae with a shell, or test, made of silica.
- Chapter 5, p. 94; Figure 5.6

Coccolithophorids Single-celled algae covered with plates made of calcium carbonate.
- Chapter 5, p. 97; Figure 5.10

Foraminiferans (Forams) Protozoans, often microscopic, with a calcium carbonate shell.
- Chapter 5, p. 97; Figure 5.11

Radiolarians Single-celled protozoans with a test made of silica.
- Chapter 5, p. 98; Figure 5.12

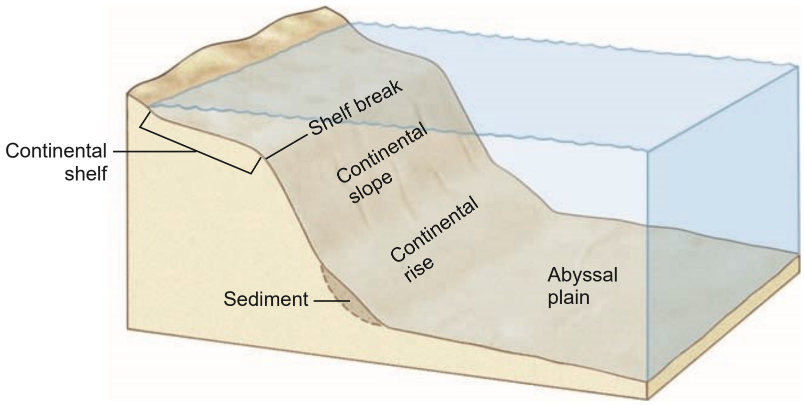
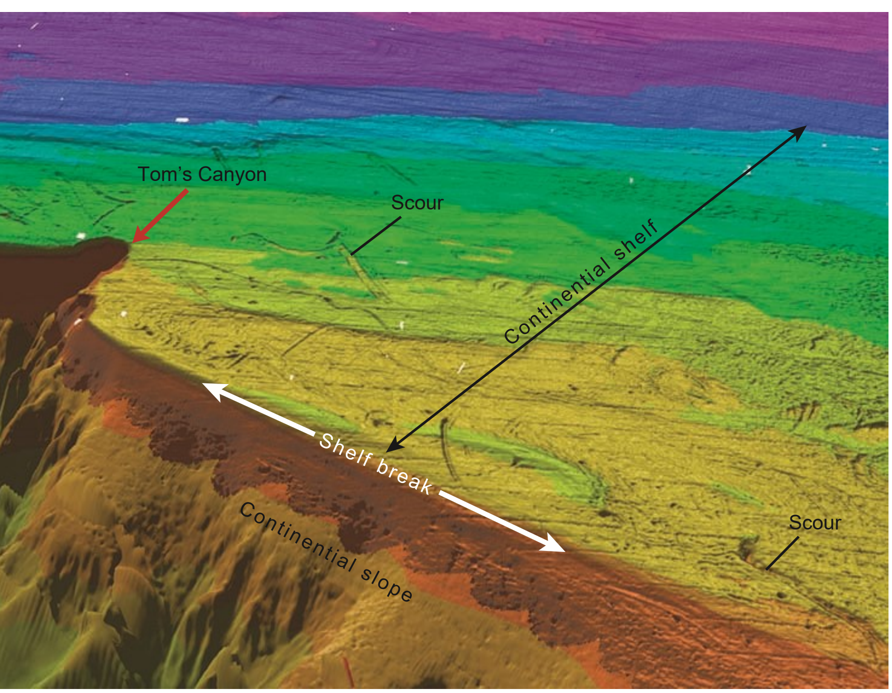


FIGURE 2.19 An idealized continental margin consists of a continental shelf, continental slope, and a continental rise. Seaward of the continental rise lies the deep-sea floor, or abyssal plain. These basic features vary from place to place.

The Continental Shelf The shallowest part of the continental margin is the continental shelf. Though they make up only about 8% of the ocean's surface area, continental shelves are the biologically richest part of the ocean, with the most life and the best fishing. The shelf is composed of continental crust and is really just part of the continent that presently happens to be under water. During past times of low sea level, in fact, most of the continental shelves were exposed. At these times, rivers and glaciers flowed across the continental shelves and eroded deep canyons. When sea level rose, these canyons were submerged and gave rise to much larger **submarine canyons.**

The continental shelf extends outward at a gentle slope that in most places is too gradual to see with the naked eye. The shelf varies in width from less than 1 km (0.6 mi) on the Pacific coast of South America and other places to more than 750 km (470 mi) on the Arctic coast of Siberia. The continental shelf ends at the **shelf break,** where the slope abruptly gets steeper (Fig. 2.20). The shelf break usually occurs at depths of 120 to 200 m (400 to 600 ft) but can be as deep as 400 m (1,300 ft).

FIGURE 2.20 A section of the continental shelf (upper right) off Atlantic City, New Jersey, approximately 30 km (19 mi) wide. The white arrows indicate the shelf break. The red arrow shows the head of a submarine canyon called Tom's Canyon. The linear marks on the shelf are iceberg scours made during the last ice age. This image was created with a sophisticated form of sonar known as multibeam sonar. The steepness of the continental slope is exaggerated.



The Continental Slope The continental slope is the closest thing to the exact edge of the continent. It begins at the shelf break and descends downward to the deep-sea floor. Submarine canyons beginning on the continental shelf cut across the continental slope to its base at a depth of 3,000 to 5,000 m (10,000 to 16,500 ft; Fig. 2.21). These canyons channel sediments from the continental shelf to the deep-sea floor.

The Continental Rise Sediment moving down a submarine canyon accumulates at the canyon's base in a deposit called a **deep-sea fan,** similar to a river delta. Adjacent deep-sea fans may merge to form the continental rise. The rise consists of a thick layer of sediment piled up on the sea floor. Sediment may also be carried along the base of the slope by currents, extending the continental rise away from the deep-sea fans.

Continental margins have three main parts. The continental shelf is the submerged part of the continent and is almost flat. The relatively steep continental slope is the actual edge of the continent. The continental rise is formed by sediments building up on the sea floor at the base of the continental slope.

Active and Passive Margins The nature of the continental margin, and therefore of the biological habitats on the coast, depends to a large extent on the plate tectonic processes occurring in the region. The continent of South America provides a good example of the relationship between the continental margin and plate tectonics (Fig. 2.22). The South American Plate (see Fig. 2.10) consists of both the continent itself and the part of the Atlantic sea floor created by the Mid-Atlantic Ridge. South America is carried westward along with the plate as new sea floor is created in the Atlantic. The west coast of South America is colliding with the Nazca Plate, leading to the creation of a trench (see Figs. 2.5 and 2.11). Trenches are zones of intense geological activity, including earthquakes and volcanoes, so this type of continental margin is called an **active margin.** The west coast of North America also has a type of active margin, but it is much more complex than that of South America.

As the colliding plate descends into the trench, some of the sediment gets scraped off, folded, and “plastered” onto the continental margin. The edge of the continent is lifted by the oceanic plate passing below (see “Sea-Floor Spreading and Plate Tectonics,” p. 27), and the coast is built up by volcanoes. These processes give active margins steep, rocky shorelines (Fig. 2.23), narrow continental shelves, and steep continental slopes. Because the sediments at the base of the continental slope are either carried down into the trench or scraped onto the continent, active margins usually lack a well-developed continental rise.

South America’s east coast, on the other hand, is not a boundary between plates and is therefore relatively inactive geologically. The continental margin here can be thought of as the trailing edge left when South America separated from Africa. This type of margin is called a **passive margin.** Passive margins typically have flat

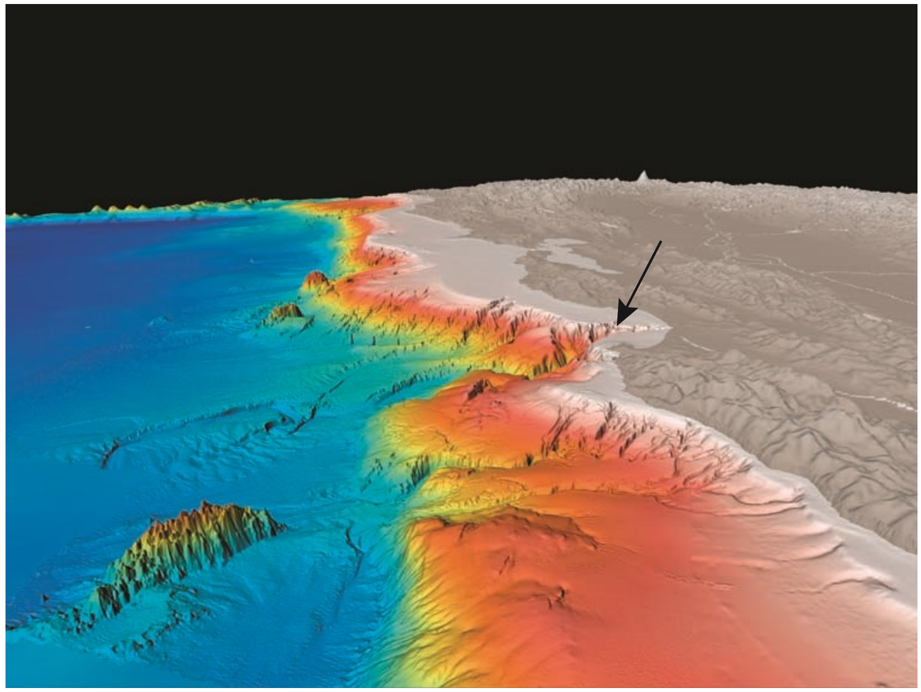


FIGURE 2.21 Multibeam sonar image of the continental margin off California. A number of submarine canyons cut across the continental shelf and down the continental slope to the deep-sea floor. The largest is Monterey Canyon, which extends nearly to the shore at Monterey Bay (arrow).

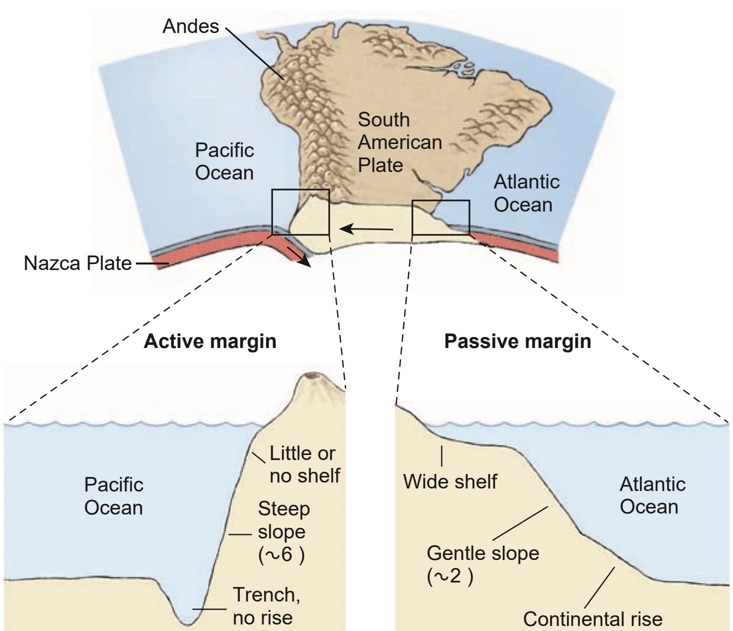


FIGURE 2.22 The opposite sides of South America have very different continental margins. The leading edge, or west coast, is colliding with the Nazca Plate. It has a narrow shelf and steep slope and has a trench rather than a continental rise. The trailing edge—that is, the Atlantic coast—has a wide shelf, a relatively gentle continental slope, and a well-developed continental rise. The steepness of all the slopes is exaggerated for illustrative purposes. Compare this with the map in Figure 2.5.

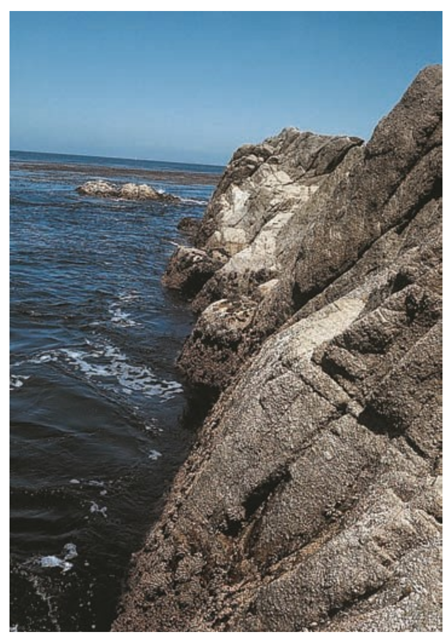
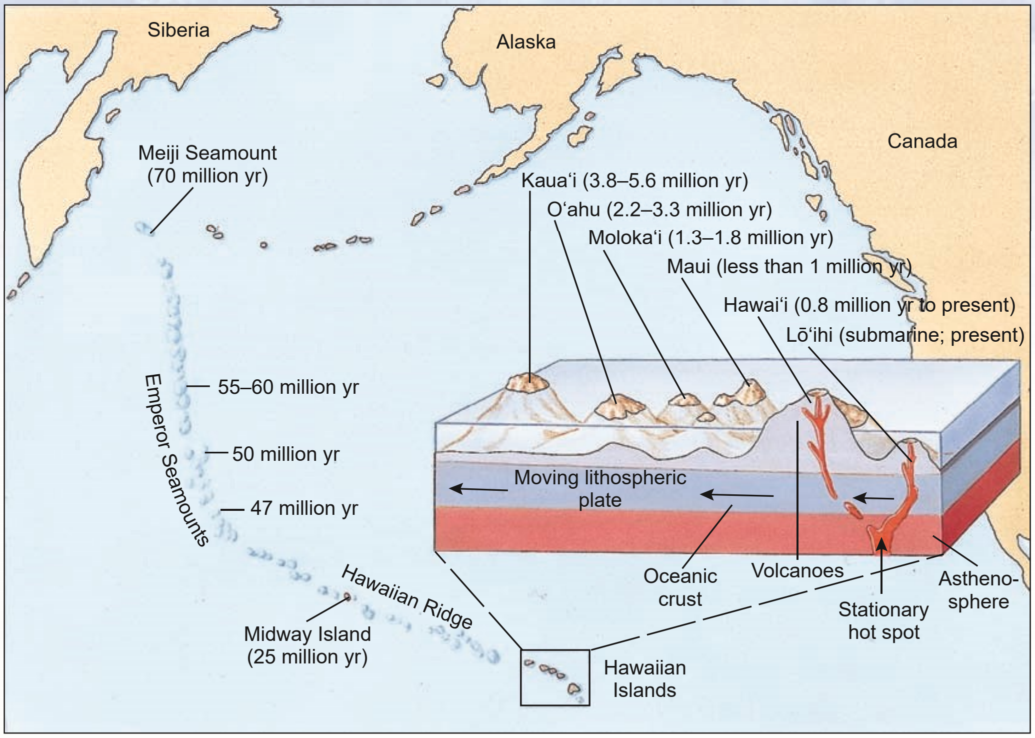


FIGURE 2.23 Steep, rocky shorelines like this one along the Pacific coast of North America at Monterey, Bay, California, are typical of active margins, although they occur in other places. The special problems of the organisms living on shores like this are discussed in Chapter 11.

The Hawaiian Islands, Hot Spots, and the Great Mantle Plume Debate



The Emperor Seamounts and Hawaiian Island chain. Some geologists think that the chain was formed not by a hot spot as shown here but by a crack in the lithosphere.

The Hawaiian Islands are part of a chain of volcanoes called the Hawaiian Ridge, which is connected to a string of seamounts stretching to the northwest called the Emperor Seamount chain. The volcanoes get progressively older along the chain. A young submarine volcano called Lō'ihi lies southeast of the island of Hawai'i, the youngest Hawaiian island, and could grow into a new island. Hawai'i began forming less than a million years ago and is still erupting. Much of the island is bare volcanic rock too young to have eroded or for vegetation to grow. Kaua'i, at more than 5 million years old, is the oldest of the main Hawaiian Islands. It is densely vegetated, and erosion has

coastal plains (Fig. 2.24), wide shelves, and relatively gradual continental slopes. Because there are no tectonic processes to remove it, sediment accumulates at the base of the continental slope. Passive margins therefore usually have a thick continental rise.

FIGURE 2.24 The Atlantic coast of North America has a passive margin. Because of the lack of geological activity and the buildup of sediments, most of the eastern seaboard has a broad coastal plain, with barrier islands, salt marshes, lagoons, and estuaries.

Active continental margins have narrow shelves, steep slopes, and little or no continental rise. Passive margins have wide shelves, relatively gentle slopes, and a well-developed rise.

Deep-Ocean Basins

Most of the deep-sea floor lies at a depth of 3,000 to 5,000 m (10,000 to 16,500 ft), averaging about 4,000 m (13,000 ft). The deep-sea floor, or **abyssal plain,** rises at a very gentle slope of less than 1 degree toward the mid-ocean ridge. Though relatively flat, it often has submarine channels, low **abyssal hills,** plateaus, rises, and other features. The abyssal plain is dotted with volcanic islands and submarine volcanoes called **seamounts.** Distinctive flattopped seamounts called **guyots** (pronounced "*gee*-ohs") are common in parts of the Pacific. Guyots and many other seamounts were once islands, but are now several hundred meters beneath the sea surface

Volcanic eruption at Kilauea, Hawai‘i.

produced steep, jagged cliffs. The remaining islands and seamounts of the chain continue to get older moving to the northwest. Midway, about two-thirds of the way up the Hawaiian Ridge, is about 25 million years old. Meiji Seamount, at the northernmost end of the chain, is 70 million years old.

This pattern is widely attributed to a hot spot, a place where a plume of hot magma rises from deep in the mantle and forces its way through the lithosphere to erupt in volcanic activity. As the Pacific Plate moves over the stationary hot spot, each new eruption of magma breaks out at a slightly different place, producing the line of volcanoes. The bend between the Hawaiian Ridge and the Emperor Seamounts is thought to have occurred when the Pacific Plate changed direction.

Geologists have identified around 50 other hot spots around the world. Most are under oceanic plates. Hot spots are credited for other island-seamount chains in the Pacific Ocean; the Gilbert and Tokelau chains even have bends like the Hawaiian-Emperor chain. Hot spots associated with mid-ocean ridges and hence not under moving plates are thought to have created single islands or groups of islands rather than chains. Examples include Iceland, the Azores, and the Galápagos Islands. There are also a few hot spots beneath continents. The most famous is associated with the geysers and bubbling pools of Yellowstone and a line of progressively older volcanoes to the northwest. Geologists hypothesize that even larger masses of hot magma called superplumes also rise from deep in the mantle, lifting up great areas of lithosphere. A superplume is thought to have uplifted a vast plateau region in southern Africa, for example.

Mantle plumes and hot spots are accepted by most geologists, but a minority are skeptical. Some think current ideas about mantle plumes and hot spots need major overhaul, while others deny that plumes and hot spots exist at all. They argue that the pressure deep in the mantle is far too great to allow mantle plumes to rise, and point out that there is little sign of the unusual heat deep in the mantle that should underly hot spots. If the bends in the Hawaiian-Emperor, Gilbert, and Tokelau chains formed when the Pacific Plate changed direction, as claimed by the hot spot hypothesis, they should all be the same age. The Hawaiian-Emporer and Gilbert bends are both estimated to be around 47 million years old, but the bend in the Tokelau chain is estimated at 57 million years. This and other evidence suggests that hot spots move from place to place, contrary to the long-held hypothesis that they remain stationary under the moving plates.

Mantle plume skeptics argue that the volcanic activity attributed to hot spots actually occurs because unusual stress or weakness in the lithospere causes a plate to crack, allowing magma to well up from the shallow—not deep—mantle. They explain island chains by rifts in the lithosphere that gradually extend like a crack in a windshield. They propose that Iceland formed not over a hot spot but at a weakened, ancient fault where North America and Europe collided 400 million years ago as part of the formation of Pangaea.

The debate over mantle plumes and hot spots shows no signs of abating, but both sides can explain an unusual feature of the Hawaiian Islands. About a quarter of the shallow-water fish species and one-fifth of shallow-water molluscs there are endemic, meaning they are found nowhere else. This is one of the highest rates of marine endemism anywhere, but even the oldest island, Kua‘i, at only 5 million years old, is far too young for so many unique species to have evolved there. These species probably originated on much older islands in the chain. As the islands sank to become seamounts, the animals moved to shallow waters on newer islands that appeared nearby, whether because of a hot spot or a crack in the crust.

because the lithosphere has sunk into the mantle under the weight of the island, and also because sea level has risen. The abyssal plain and seamounts are home to a tremendous variety of marine life (see “Biodiversity in the Deep Sea,” p. 375).

At trenches, where the plate descends into the mantle, the sea floor slopes steeply downward. Trenches are the deepest parts of the world ocean. The Mariana Trench in the western Pacific is the deepest place of all, at 11,022 m (36,163 ft) deep.

The Mid-Ocean Ridge and Hydrothermal Vents

The mid-ocean ridge itself is an environment that is unique in the ocean. As noted previously, the ridge is formed when material rising from the mantle pushes up the oceanic crust. Right at the center of the ridge, however, the plates are pulling apart. This leaves a great gap or depression known as the **central rift valley.** The floor and sides of the valley are riddled with crevices and fractures. Seawater seeps down through these cracks until it gets heated to very high temperatures by the hot mantle material (Fig. 2.25). The heated water then forces its way back up through the crust and emerges in **hydrothermal vents,** or deep-sea hot springs.

The water coming from many hydrothermal vents is warm, perhaps 10° to 20°C (50° to 68°F), much warmer than the surrounding water (see “The Three-Layered Ocean,” p. 53). At some vents, however, the water is blisteringly hot, up to 350°C (660°F). The water is so hot that when scientists first tried to measure its temperature the thermometer they were using started to melt! To take accurate readings, they had to return with a specially designed thermometer.

As the hot water seeps through cracks in the earth’s crust, it dissolves a variety of minerals, mainly **sulfides.** When the mineral-laden hot water emerges at the vent, it mixes with the surrounding cold water and rapidly cools. This causes many of the

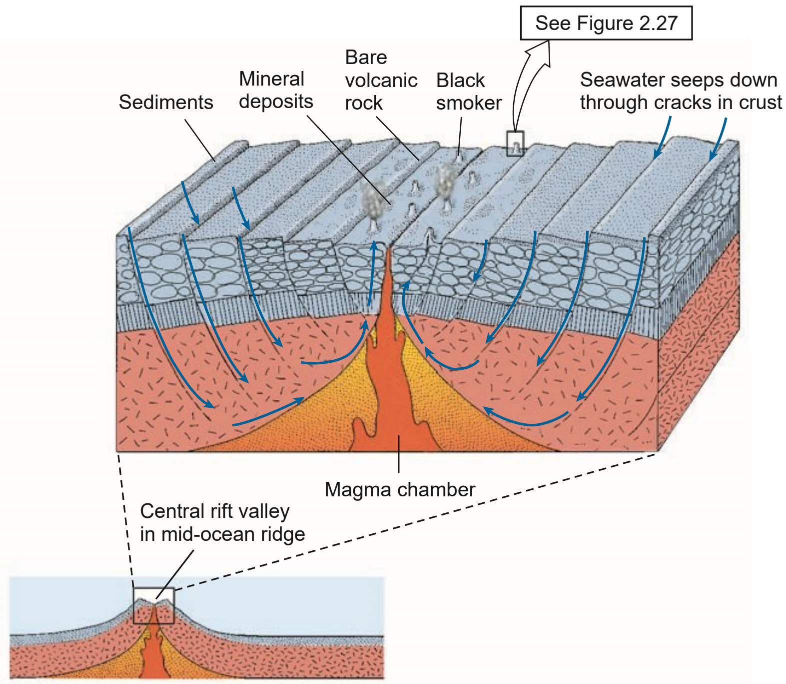


FIGURE 2.25 A cross section of a mid-ocean ridge showing how seawater seeps down through cracks in the crust, is heated, and reemerges in underwater hot springs.

minerals to solidify, forming mineral deposits around the vents. **Black smokers** (Figs. 2.26 and 2.27) are one type of deposit found at hydrothermal vents. These are chimney-like structures that progressively build up around a vent as the minerals solidify. The "smoke" is actually a dense cloud of mineral particles.

When hydrothermal activity was first discovered it was thought to be confined to mid-ocean ridges. Hydrothermal vents, complete with black smokers and other mineral deposits, have since been found behind trenches. They result from the same volcanic activity that creates island arcs (see "Sea-Floor Spreading and Plate Tectonics," p. 27). Relatively cool (40° to 75°C, or 105° to 170°F) vents have also been discovered near, but not at, mid-ocean ridges. These vents produce chimneys of carbonate rather than sulfide minerals and are caused by chemical reactions between seawater and newly formed oceanic crust rather than by volcanic activity. One such chimney rises 60 m (200 ft) above the sea floor, making it the tallest hydrothermal vent known.

Deep-sea hot springs are of great interest not only to geologists, but also to biologists. The discovery of unexpectedly rich marine life around hydrothermal vents was one of the most exciting finds in the history of marine biology. These organisms are discussed in Chapter 16 (see "Hot Springs, Cold Seeps, and Dead Bodies," p. 374).

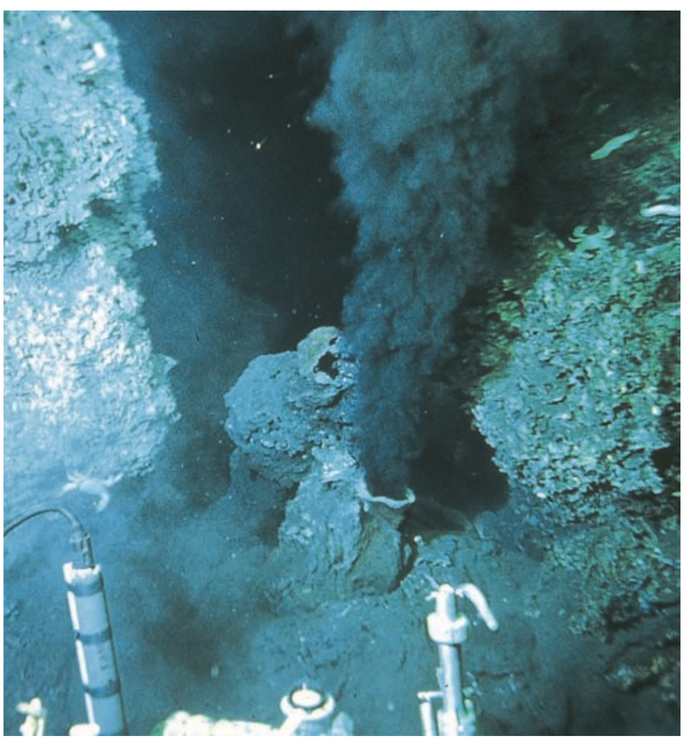


FIGURE 2.26 Black smokers are common in hydrothermal vent areas. The black "smoke," actually composed of mineral particles, rises because the water emerging from the black smoker is much warmer than the surrounding water. This photo was taken at the Galápagos vent, a part of the East Pacific Rise. The instruments in the foreground belong to *Alvin,* from which the photo was taken.

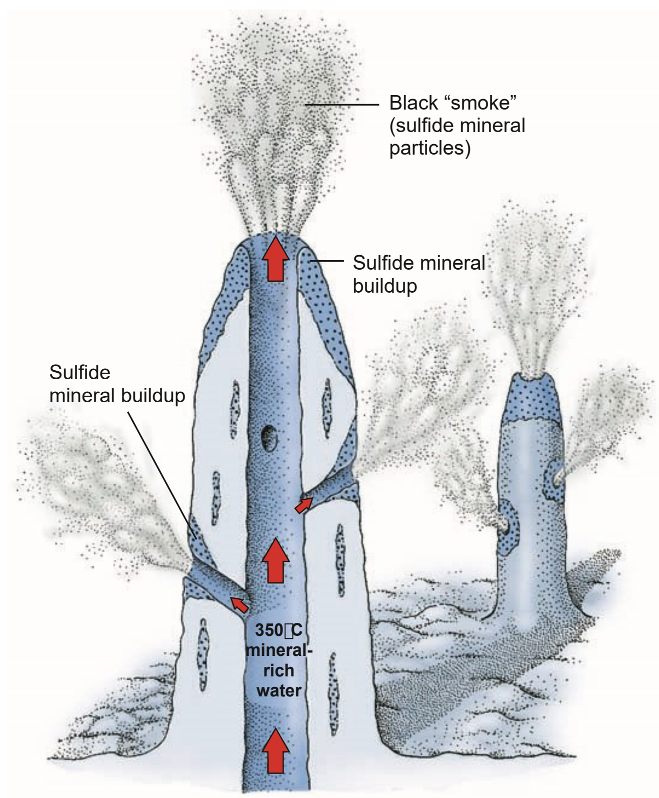


FIGURE 2.27 Cross section of a black smoker. Minerals are deposited as a precipitate when hot, mineral-laden water emerging from the rift zone meets the cold ocean water. Over time these mineral deposits build up the chimney of the black smoker.