19 Divergent Plate Boundaries

Although we have studied the ocean and used its resources for thousands of years, until now the details of the ocean floor have remained mysterious. Using sophisticated radar instruments carried by satellites, we have constructed for the first time accurate maps of the ocean floor that reveal the dominant role played by divergent plate boundaries among Earth's dynamic systems.

The ocean ridge is part of the global system of divergent plate boundaries that encircles the planet. High mountainous ridges coincide with these boundaries and extend through all of the ocean basins in a nearly continuous seam that is tens of thousands of kilometers long. Oceanic ridges are the sites of the most active volcanism on Earth. Occasionally, the rift valleys become boiling cauldrons when basalt, fresh from the mantle, erupts from long fissures onto the ocean floor. The volcanic rocks of the high ridge are so hot and porous that seawater easily circulates through the crust. Where the water exits, dense plumes of hot

water belch from fragile chimneys that rise as high as skyscrapers. Here the crust is so active that its movement away from the ridge can be measured in centimeters per year.

The panorama above shows the oceanic ridge where it rises above sea level in Iceland. The entire area is built of floods of young basalt cut by a shallow rift valley extending through the center. A shallow lake partially fills the graben. The long linear fissures formed during rifting between volcanic episodes. Shallow earthquakes rattle the country during volcanic eruptions and rifting episodes. The road snakes its way from the high rift flank across a tensional fracture and onto the floor of the broad rift valley. In fact, tour buses, like the one on the road, can take visitors from the North American plate, on the right, across the rift to the Eurasian plate on the left.

Throughout Earth's long history, the geologic processes operating at divergent plate boundaries have been among the most fundamental forces that shaped our world. It is at divergent plate boundaries that continents split and move apart, creating new continental margins, many of which contain valuable resources such as petroleum, natural gas, and salt. In this chapter, we examine these divergent plate boundaries as parts of Earth's plate tectonic system. We first study the role they play in the formation of oceanic crust and then explore how they form when continents split and move apart to form new ocean basins.

Photograph by Motomaro Shirao.

MAJOR CONCEPTS

1. Divergent plate boundaries are zones where lithospheric plates move apart from one another. They are characterized by tensional stresses that typically produce long rift zones, normal faults, and basaltic volcanism.
2. An oceanic ridge marks divergent plate boundaries in the ocean basins. It is a broad, fractured swell with a total length of about 70,000 km. Basaltic volcanism and shallow earthquakes are concentrated along the rift zone at the ridge crest.
3. The ridge's characteristics depend upon the spreading rate. As oceanic lithosphere moves away from the ridge, it cools, becomes thicker and denser, and subsides.
4. Oceanic crust is generated at divergent plate boundaries and is composed of four major layers: (a) deep marine sediment, (b) pillow basalts, (c) sheeted dikes, and (d) gabbro. Below the crust lies a zone of sheared peridotite in the upper mantle.
5. At divergent plate boundaries, basaltic magmatism results from decompression melting of the mantle. The magma then collects into elongate chambers beneath the ridge, and some is intruded as dikes or extruded along the rift zone.
6. Seawater is heated as it circulates through the hot crust and causes extensive metamorphism. Locally, the hydrothermal fluids produce hot springs on the seafloor.
7. Continental rifting occurs where divergent plate margins develop within continents. The East African Rift, the Red Sea, and the Atlantic Ocean illustrate the progression from continental rifting to seafloor formation.
8. Continental rifting creates new continental margins marked by normal faults and volcanic rocks interlayered with thick sequences of continental sedimentary rocks. As the continental margin subsides, it is gradually buried beneath a thick layer of shallow-marine sediments.

MIDOCEANIC RIDGES

A midoceanic ridge marks a divergent plate boundary in an ocean basin. It is a broad, fractured swell, marked by basaltic volcanism and earthquakes. As the oceanic lithosphere moves away from the ridge, it cools, becomes thicker and denser, and subsides.

The discovery of divergent plate margins only a few decades ago changed forever our understanding of Earth's dynamics. It is along divergent plate margins that the longest and most important mountain chain of our planet is located (Figure 19.1). Beneath divergent plate margins chambers are filled with hot magma that is episodically extruded to form new oceanic crust.

The creation of new oceanic crust is the fundamental process that occurs at a **midocean ridge.** Indeed, more rock is generated at this type of divergent plate boundary than by all other processes combined. Since the early periods of Earth's history, igneous activity along divergent plate margins has generated enough basalt to cover the entire Earth with a layer about 120 km thick. As new crust forms, however, it continually spreads away from the ridge crest at rates of several centimeters per year. The newly formed basaltic crust is cooled by circulating seawater at a rate sufficient to filter the entire ocean's water within a few million years. These circulating waters alter the hot oceanic crust, thereby creating large volumes of metamorphosed basalt.

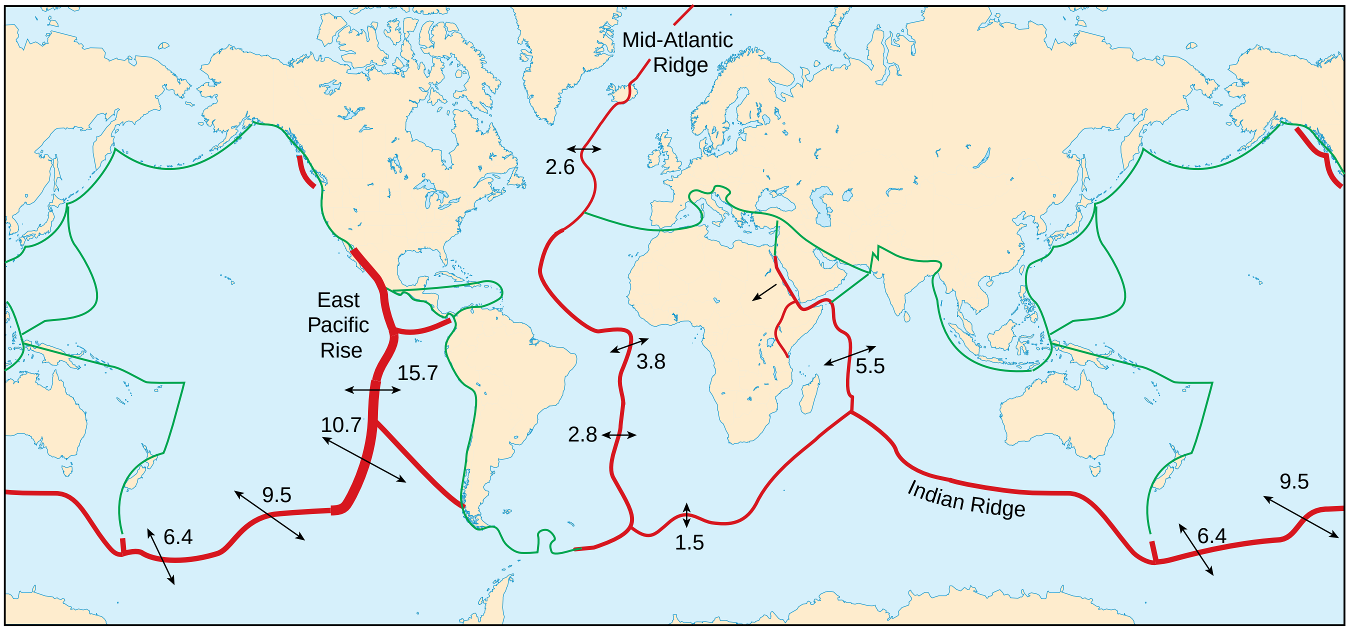
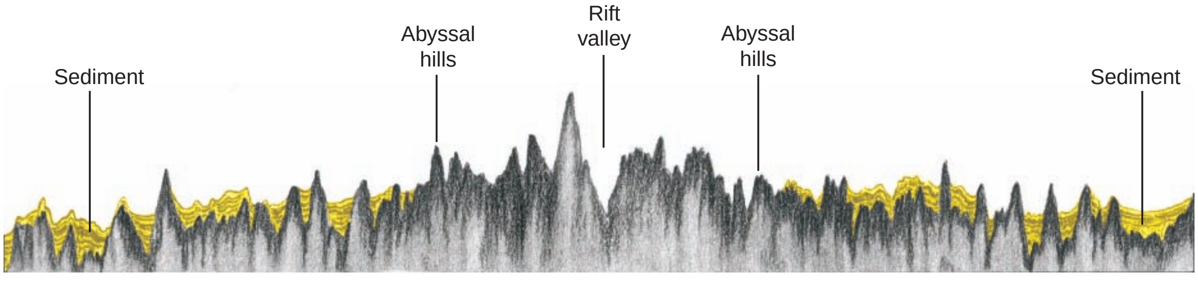


FIGURE 19.1 **The midocean ridge** (red) extends as a major structural feature around the entire globe and marks divergent plate boundaries. The thickness of the line is proportional to the rate of spreading. The numbers give spreading rates in cm/y. Note the rate of spreading along the Mid-Atlantic Ridge is slow, so the ridge is high and rugged and is cut by a deep rift valley. The ridge in the eastern Indian Ocean spreads at an intermediate rate. The East Pacific Rise typically spreads at 15 cm/yr, about six times faster than the Mid-Atlantic Ridge.

Methods of Study

Our new knowledge of the ocean floor comes from a variety of direct and indirect observations. One is the use of sophisticated sonar equipment, which provide images of the ocean floor similar to relief maps of the continents made from aerial photography. In addition, the sound waves penetrate the upper layers of the oceanic crust, revealing its internal structure (Figure 19.2). Numerous dredge and drill-core samples have been obtained from specially designed oceanographic ships. Closeup examination of the seafloor from divers in small submarines also has revealed much about this concealed part of our planet. Only small parts of the oceanic ridge are exposed above sea level, allowing direct examination of the processes that create oceanic crust even as it forms. However, a few large segments of ancient oceanic crust have been thrust up and over continental rocks where geologists can study oceanic crust on dry land.

How do we "see" the topography and landforms of the ocean floor?



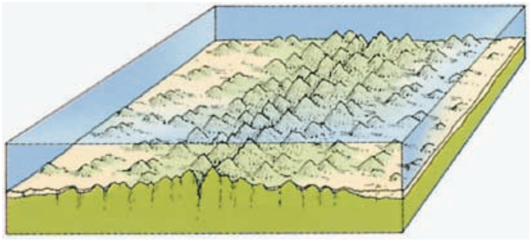


FIGURE 19.2 **Seismic reflection profiles of the midocean ridge** provide some of the fundamental data concerning the topography and the characteristics of divergent plate margins. A profile across the Mid-Atlantic Ridge at 44° north shows the outline of the surface plus the subsurface structure. The crest of the ridge is marked by a deep rift valley, which can be traced along most of the Mid-Atlantic Ridge. Note the layers of marine sediment along the flanks of the ridge and their absence at the ridge crest. The vertical scale is greatly exaggerated for this 500-km-long transect.

These direct studies are supplemented by various indirect studies using geophysical measurements such as paleomagnetism, seismicity, gravity, and heat flow. These geophysical measurements give us the ability to "see" not only the surface of the ocean floor, but also the internal structure of the oceanic crust. In the last few years, declassified sea surface measurements collected by military satellites have been converted to topographic maps covering nearly all of Earth's ocean floor (see the inside cover). All of these observations combine to provide a firm basis for constructing models of how divergent plate margins operate.

Topography of Midocean Ridges

The oceanic ridges are the most pronounced tectonic features on Earth. If they were not covered with water, the ridges would be visible from the Moon. A midoceanic ridge is essentially a broad, fractured swell, a huge feature generally more than 1500 km wide (the width of Texas), with peaks rising as much as 3 km above the surrounding ocean floor. Its local relief is thus greater than some mountain ranges on land.

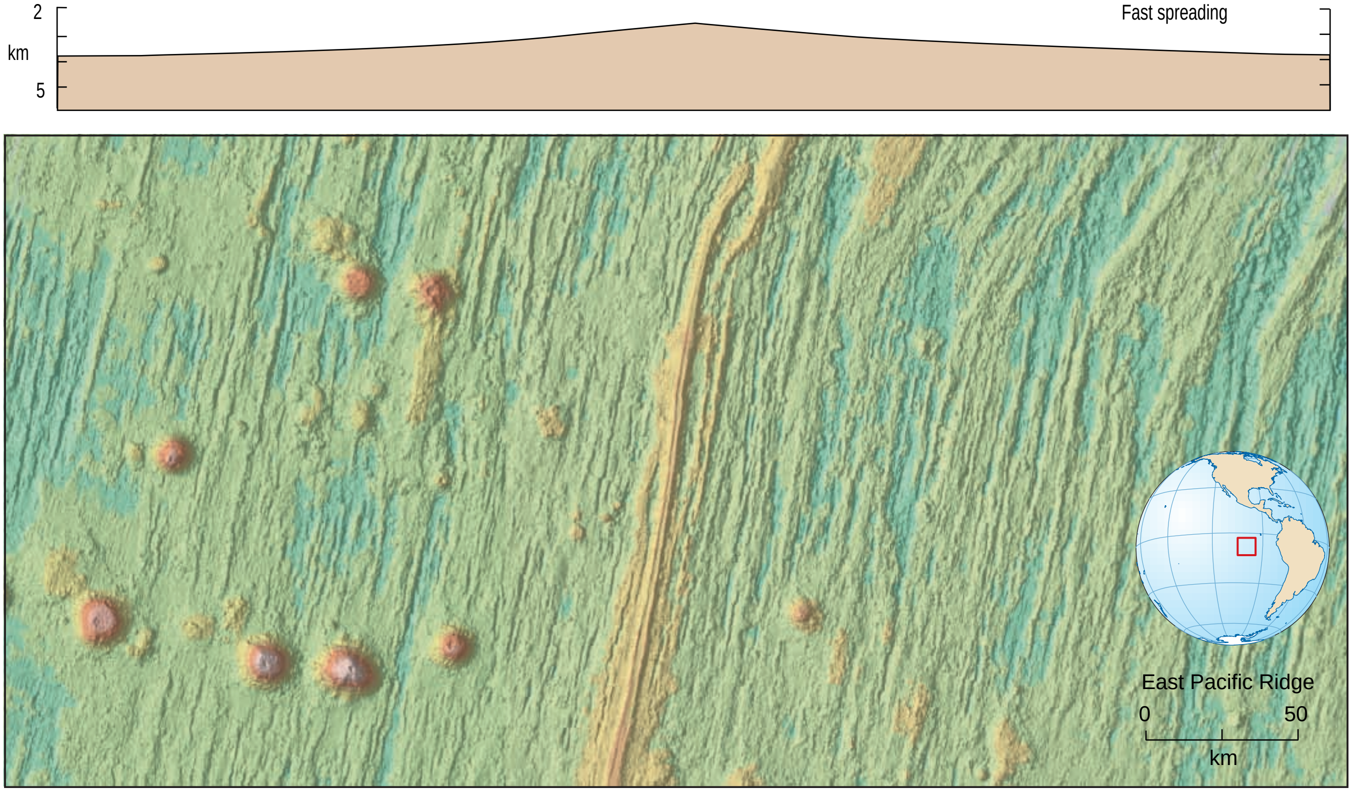
Remarkably, the midoceanic ridge is a nearly continuous feature around the entire globe, like the seam of a baseball (Figure 19.1). The ridge extends from the Arctic Basin, down through the center of the Atlantic, into the Indian Ocean, and across the South Pacific, ending in the Gulf of California, a total length of about 70,000 km. Without question, it is the greatest "mountain" system on Earth. The internal structures of the "mountains" of the oceanic ridge, however, are nothing like the mountains of the continents, which largely consist of folded and metamorphosed sedimentary rocks. By contrast, the ridge is composed entirely of basalt and is not deformed by folding. Its main structures are due to extensional forces, resulting in normal faulting and basaltic igneous activity. The midocean ridge is not one continuous fracture. It is broken into segments defined by offsets (Figure 19.3B). Many involve **transform faults** and their extensions called **fracture zones,** which are some of the most prominent features on the ocean floor. Small overlaps and minor bends also create irregularities in the trend of the ridge (Figure 19.4).

Many detailed characteristics of the ridge are apparent in Figure 19.5, which shows the Juan de Fuca Ridge. You can see that the broad ridge is arched up and broken by many faults, which form linear hills and valleys. The highest and most rugged topography is along the axis, and a prominent **rift valley** marks the crest of some ridges throughout much of their lengths. Locally, volcanoes have completely filled the rift valley and rise above its crest. The East Pacific Rise displays much less rugged topography and does not possess a prominent central rift valley (Figure 19.3A). Oceanic sediments are thickest on the flanks of the ridge, but they thin rapidly toward the crest (Figure 19.2).

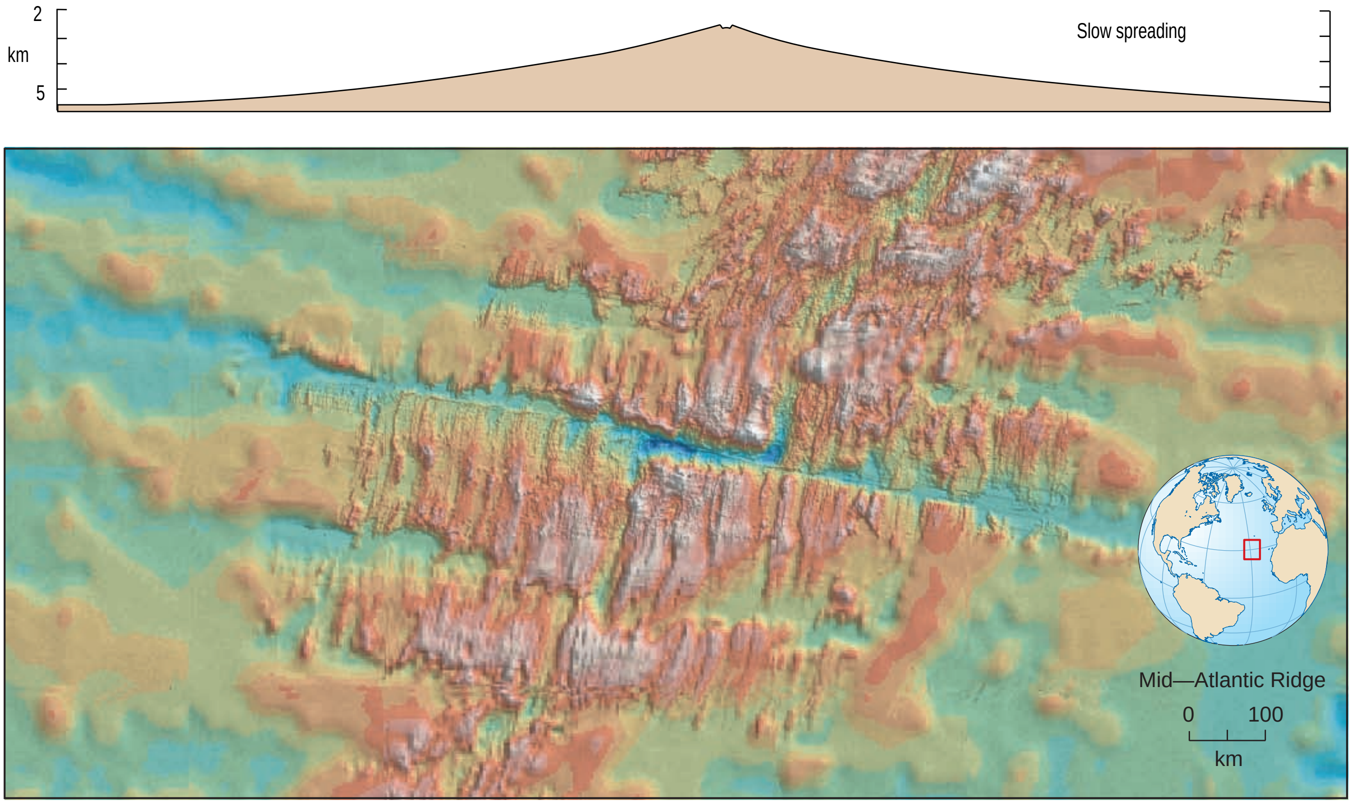
The characteristics of a ridge depend on its **spreading rate.** Where the rate of spreading is slow (less than 5 cm/yr), as in the North Atlantic (Figure 19.1), the oceanic ridge is steeper and more rugged and mountainous, and a prominent rift valley develops along the axis (Figure 19.3B). At intermediate spreading rates (5 to 9 cm/yr), as in the southern part of the Indian Ocean Ridge, the topography is more subdued and the rift valley is only 50 to 200 m deep. At faster spreading rates (greater than 9 cm/yr), as in the eastern part of the East Pacific Rise, the ridge topography is relatively smooth and no rift valley develops (Figure 19.3A).

Regardless of spreading rates, however, all ridge crests are marked by a zone of volcanic activity and fissures (Figure 19.5). Away from the ridge crest, the topography is controlled by active normal faults. Some 10 to 15 km from the axis, there is little volcanic activity or faulting. Thus, the actual plate boundary, the place of intense geologic activity, is a narrow zone only 20 to 30 km wide.

Cooling and Subsidence of Oceanic Crust. The elevation of the ocean floor is strongly influenced by its temperature. This simple observation is the result of an



(A) Fast-spreading ridges, such as the East Pacific Ridge, usually have gentle slopes and lack a prominent rift valley at the ridge crest.



(B) Slow-spreading ridges, such as the Mid-Atlantic Ridge, have steeper flanks and prominent rift valleys. Transform faults offset the ridge in numerous places.

FIGURE 19.3 **Spreading rate** helps control many features of an oceanic ridge. *(Courtesy of Lamont-Doherty Earth Observatory/Columbia University)*

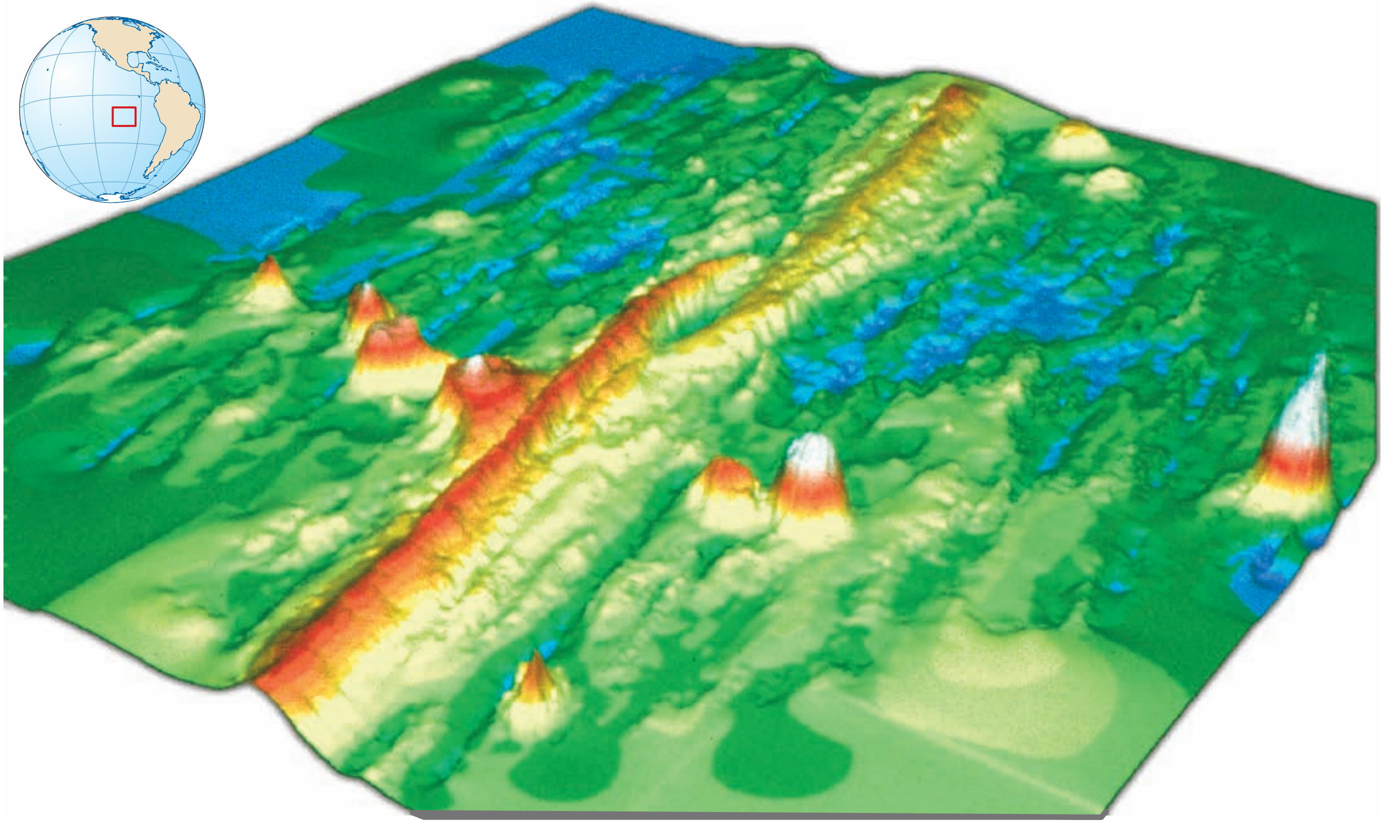


FIGURE 19.4 Overlapping ridge segments along the East Pacific Rise are shown in this color-coded topographic map. Deep-ocean floors are shown in blue, changing upward to green, yellow, red, and white. The important features in this image are the overlapping ridge segments that end in hook-shaped curves and merge with the adjacent ridge. Volcanic peaks flank the ridge. Considerable vertical exaggeration of relief is employed along this 100-km-long transect. *(Courtesy of Ken C. Macdonald, University of California, Santa Barbara)*

equally simple principle that we have repeatedly employed in our investigations of Earth systems: Hot rocks are expanded and less dense than cooler rocks of the same composition. Thus, hot rocks rise to a higher level. Because oceanic crust forms by magmatic processes at the midocean ridge, the crest of the ridge is hot. As the oceanic crust moves away from the ridge, it cools. In fact, the temperature of the oceanic crust bears a simple relationship to the distance from the spreading ridge: The farther away from the ridge, the cooler the oceanic crust.

How does the topography of the ridge in the North Atlantic differ from that of the East Pacific Rise? What causes this difference?

As a result of cooling, the oceanic crust becomes denser and subsides as it moves away from the ridge crest. Consequently, the depth to the ocean floor depends on the seafloor's age (Figure 19.6). Most studies show that the **subsidence** of oceanic crust is proportional to the square root of its age. A theoretical curve based on this heat loss model can be calculated that matches the observed depths. Water depth increases from about 2.5 km at the ridge crest to 3 km where the crust is 2 million years old, 4 km where it is 20 million years old, and 5 km where the crust is 50 million years old. In other words, the approximate age of the ocean crust can be estimated from its depth below the sea surface. Because cooling and subsidence depend on age, a fast-spreading ridge has a broader, gentler profile than a slow-spreading ridge (Figure 19.3).

An important corollary of this principle holds that there is a direct relationship between global spreading rates and sea level. If spreading rates increase, the mid-ocean ridge inflates and rises higher toward the sea surface. This expansion reduces the volume of the ocean basin, causing sea level to rise. As a result, shallow seas spill onto the stable platforms of the continents. Conversely, if seafloor spreading rates drop, sea level also drops, and the shallow seas withdraw from the continents. For example, a decrease in the spreading rate from 6 cm/yr to 2 cm/yr along

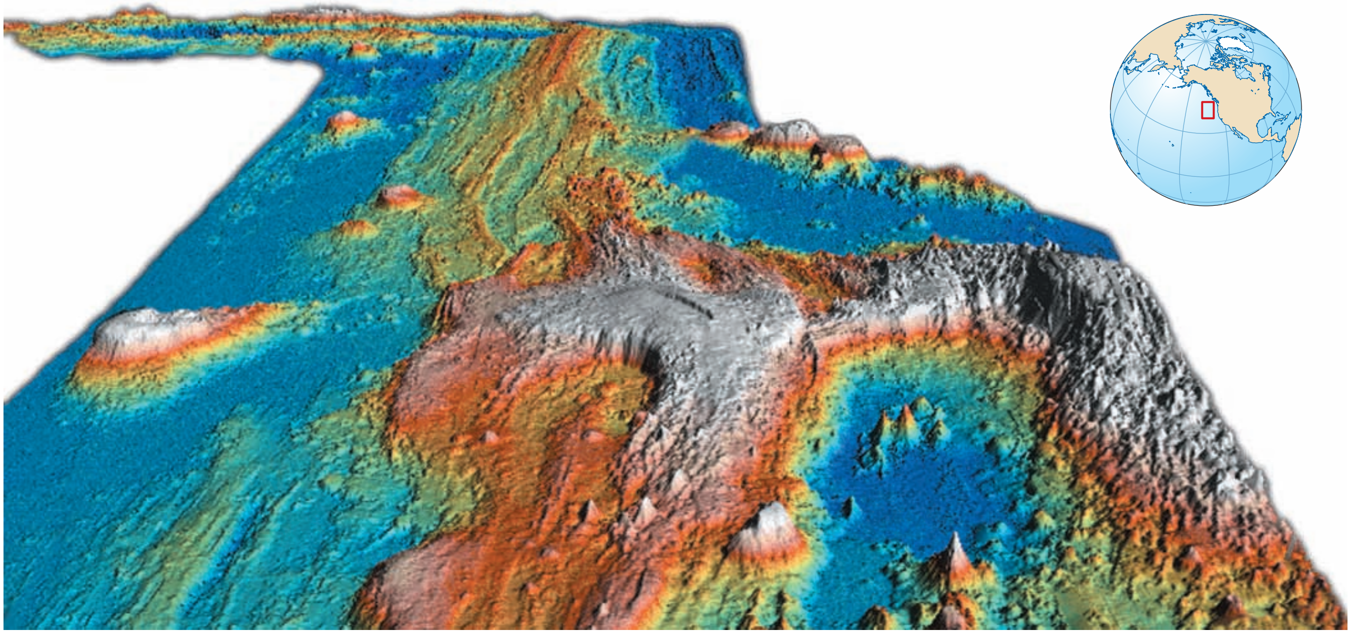


FIGURE 19.5 **Midocean ridges,** like this one along the Juan de Fuca Ridge off the coast of Washington, are regions where episodes of volcanism and tectonism alternate. The high part of this ridge is a shield volcano with a shallow summit crater. The lower parts of the ridge toward the top of the image are where volcanism is less active and normal faulting, extension, and thinning are the dominant processes, as indicated by the long linear fault blocks. Volcanic peaks or seamounts flank the rise on both plates. Near the bottom of the image, a large volcano was ripped in half by rifting. The ridge terminates near the top of the image in a long transform fault marked by a deep trough, flanked by parallel ridges. *(Courtesy NOAA PMEL Vents Program)*

a ridge that is 10,000 km long will drop global sea level by about 100 m. Such sea level changes are not rapid; they develop over tens of millions of years.

These changes in sea level may have profoundly affected the evolution of world geography throughout geologic time. Indeed, one of the great central themes of geologic history is the expansion and contraction of shallow seas over the continents, as witnessed by the numerous formations of shallow-marine sedimentary rocks that cover the stable platforms of all continents. With expanding and contracting seas, the climate and other aspects of the physical environment are significantly changed, including living space for shallow-marine and terrestrial organisms, and thus the evolution and extinction of many species are also affected.

Closeup View of the Rift Zone. Deep-sea submersibles, both piloted and robotic, have provided spectacular closeup pictures of the rift zones at divergent plate boundaries. Thousands of photographs show that the ridge surface is covered with fresh lava flows, including thin, smooth sheet flows as well as **pillow basalt.** It is important to note that almost no sediment covers even the finest details of the lava flow surfaces (Figure 19.7). This lack of cover is strong evidence that the basalt is young and fresh; otherwise, oceanic sediment would cover and mask the pillow structures. Numerous open **fissures** in the crust also exist wherever the ridge has been observed at close range (Figure 19.8). In one small area of only 6 km^2, 400 open fissures were mapped, some as wide as 3 m. These are considered conclusive evidence that the oceanic crust is being pulled apart by extension.

The eruption of lava from these fractures, which parallel the rift valley, creates long, narrow ridges, sheet flows, or small mounds of pillow lavas within the rift valley. Besides the pillow basalts and fractures, many small shield volcanoes and small fissure-fed flows dot the rift valley. In places, elongate volcanic troughs or collapsed lava lakes have been discovered by detailed mapping of the rift valley. In the rift valley, springs of hot, mineral-laden waters spew from chimneylike vents (Figure 19.9).

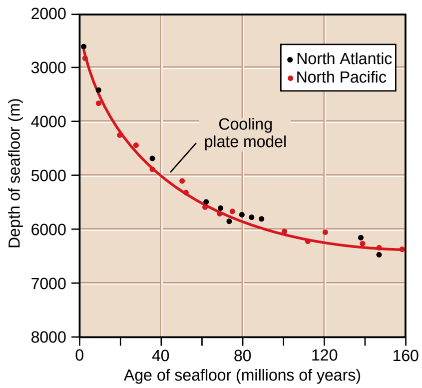


FIGURE 19.6 **Subsidence of the ocean floor** occurs as the oceanic crust cools and moves off from the ridge crest. Individual points represent the actual depth of the seafloor, and the solid line shows the calculated depth based on heat loss and contraction of oceanic lithosphere.

FIGURE 19.7 Pillow basalt along the Mid-Atlantic Ridge was photographed up close by scientists in the deep-diving submarine *Alvin*. Little or no sediment covers the basalt because this part of the seafloor is very young. The large elliptical pillow is approximately 1 m across. *(Courtesy of Woods Hole Oceanographic Institution)*

A unique and previously unknown community of living organisms thrives in the darkness of the rift valley. These ecosystems are unusual in that, unlike the rest of the known biosphere, they draw their nutrients and energy from the hot-water solutions rising from the vents rather than from sunlight. These vent communities contain 10,000 to 100,000 times more living matter than adjacent deep-sea communities and are like isolated islands of deep-marine life. Crabs, worms, shrimp, and abundant bacteria cluster around the vents. The most spectacular organisms are giant tube worms nearly 3 m long and giant clams up to 25 cm across (Figure 19.9).

Why is there little or no sediment covering the pillow basalts and sediment in the rift zone?

We should reemphasize the important fact that the active rift zone is extremely narrow, with volcanism and seafloor spreading occurring episodically in the same zone. During a rifting episode, the volcanoes and their flows are ripped asunder, roughly half going in each direction away from the center of the ridge. This activity imparts a striking symmetry to the topography and structure of the ridge—a symmetry also revealed by the paleomagnetic stripes discussed in the preceding chapter.

FIGURE 19.8 Open fissures along the Mid-Atlantic Ridge were photographed from the *Alvin*. Hundreds of such fissures were mapped. Such fissures may be as much as one meter wide and hundreds of kilometers long. They clearly show extension along the rift zone as the oceanic crust is pulling apart. *(Courtesy of Woods Hole Oceanographic Institution)*

FIGURE 19.9 **Vents for hot, mineral-laden waters** circulating through the hot rocks in the rift valley of an oceanic ridge cause black smokers. This warm water provides a unique habitat for exotic life that can subsist without sunlight. A black smoker spews hot water from a narrow chimney. The "smoke" is really dark minerals precipitating from the hot solution as it mixes with the cold ocean water. Giant tube worms and giant clams do not possess guts; they are nourished by bacteria that live in their tissues. Other life forms include white crabs, which swarm over the pillow basalt. *(Courtesy of Br. Robert McDermott, S.J.)*

As common as seafloor eruptions must be, very few have ever been observed. However, several active eruptions on the midocean ridge have been located and examined firsthand by use of underwater listening devices, formerly used only by the military to track the movement of submarines. In 1993, 1996, and 1998 scientists were able to detect new eruptions of deep-sea volcanoes on the Juan de Fuca Ridge off the Oregon coast. In 1993 a huge plume of warm water, rising above the eruption site, was discovered by ships at the surface. A remotely piloted robot submarine was lowered 2500 m to the seafloor to photograph the area and to collect samples of fresh, glassy pillow lavas. With this new monitoring system now in place, significant advances in our understanding of midocean ridge volcanic systems are likely to come. We will finally know exactly where, when, and how often volcanic eruptions occur on the ridge.

Seismicity

A narrow belt of **shallow-focus earthquakes** coincides almost exactly with the crest of the oceanic ridge and marks the boundary between divergent plates (Figure 19.10). This zone is remarkably narrow compared with the zone of seismicity that follows the trends of young mountain belts and island arcs. Another very important difference between earthquakes at convergent and divergent boundaries is

How does seismicity on the ocean floor differ from that along a subduction zone?

their depth and size. Earthquakes along divergent plate boundaries are almost always less than 10 km deep and typically are small in magnitude.

Although the zone of seismicity along the midoceanic ridge looks like a nearly continuous line on regional maps, two types of boundaries, based on fault motion as determined from earthquakes, can be distinguished: spreading ridges and transform faults (Figure 19.10). Earthquakes at the ridge occur within, or near, the rift valley. They are associated with intrusions of basaltic magma and normal faulting. Locally, shallow earthquakes in the rift occur in swarms related to the movement of magma in dikes. Why are there no deep earthquakes at the ridges? Earthquakes do not occur at great depth beneath the ridges, even though deformation is active there. Instead, the hotter, deeper mantle deforms ductilely and does not fracture as do the cooler and more brittle materials in the upper crust.

Shallow earthquakes also follow the transform faults that connect offset segments of the ridge (Figure 19.10), but they generally are not associated with volcanic activity. Studies of fault motion in the transform zone show strike-slip displacement in a direction away from the ridge crest, in contrast to the vertical motion on normal faults in the ridge crest.

Magnetic Anomalies

Magnetic surveys of the seafloor are easily accomplished, and measurements have been carried out since the mid-1950s. Magnetometers towed behind a vessel measure the magnetic field intensity. The surveys revealed a pattern of magnetic stripes of alternating high and low **magnetic anomalies** (Figure 19.11A). These bands are remarkably persistent; many can be traced for hundreds of kilometers. Furthermore, the bands are parallel to the midocean ridges and are offset at fracture zones just as the ridge crest is. As explained in Chapter 17, these anomaly bands are caused by periodic reversals in the polarity of Earth's magnetic field during seafloor spreading (see Figure 17.10 and p. 504).

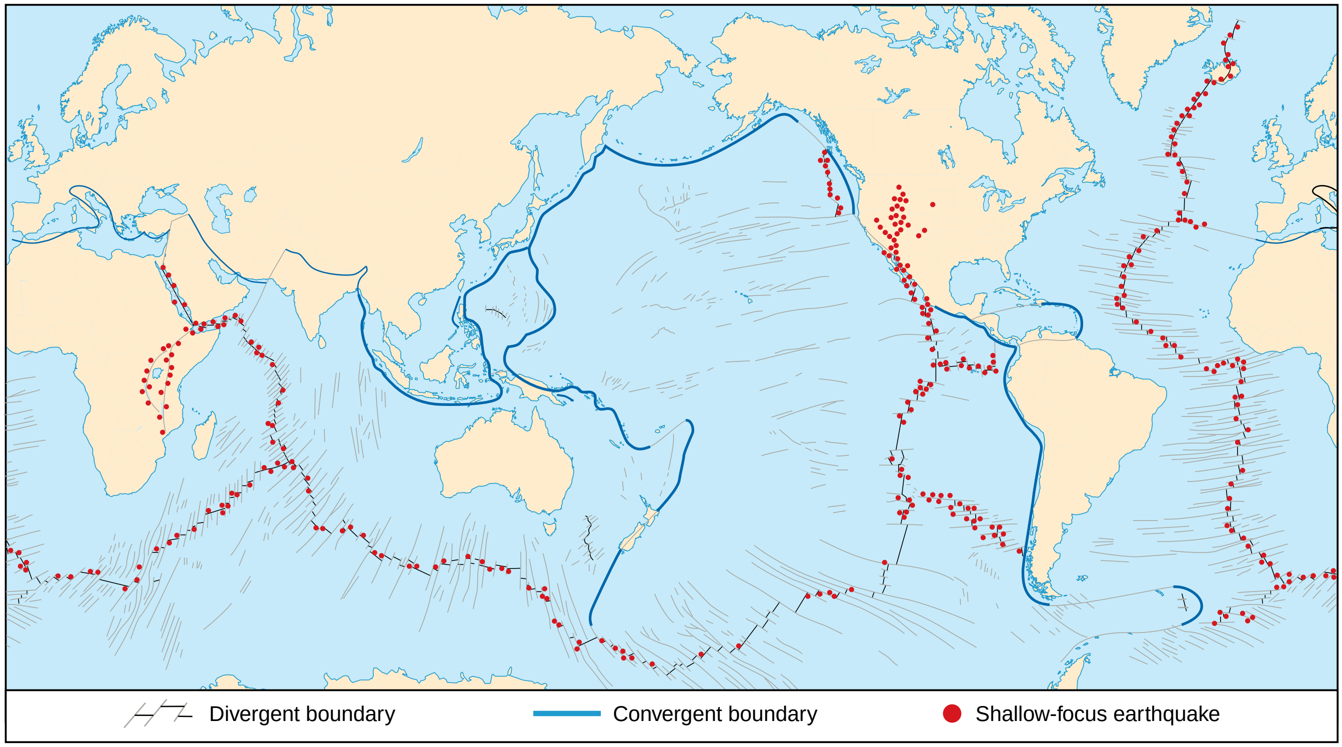


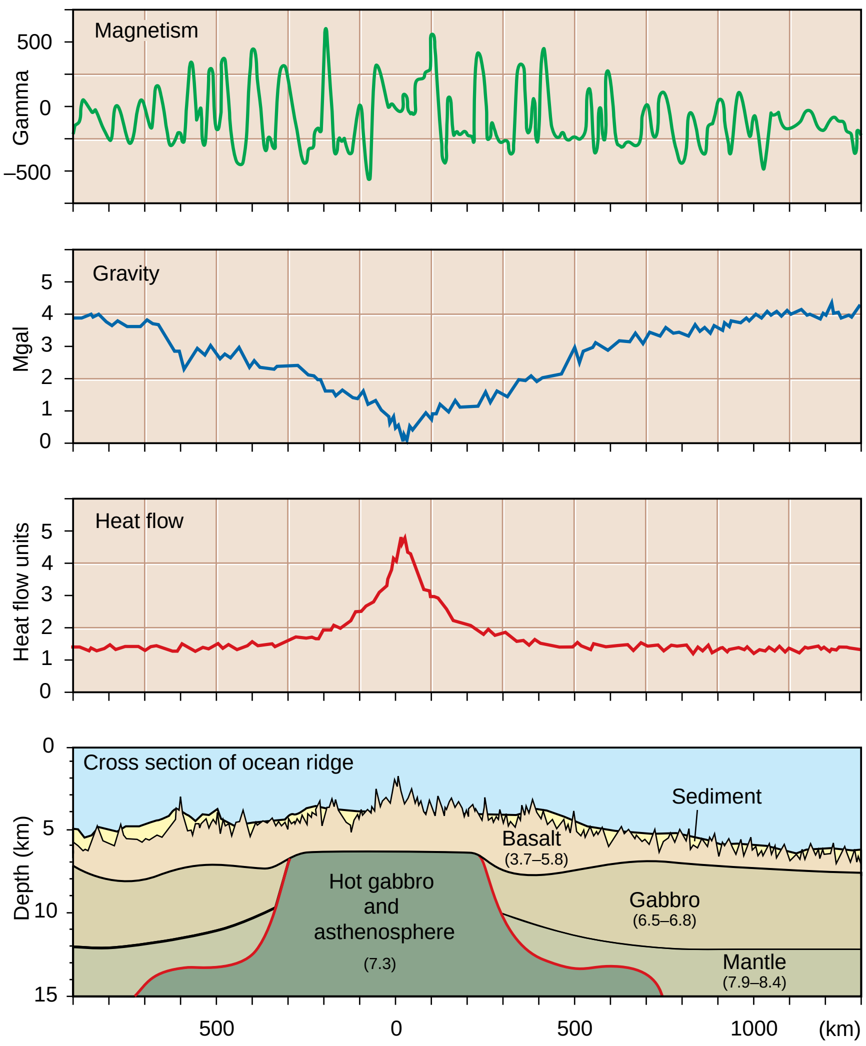
FIGURE 19.10 **Seismicity along divergent plate margins** is concentrated along the ridge crest and along transform faults. This map shows the locations of thousands of earthquakes that occurred during a 5-year period. Shallow-focus earthquakes (generally less than 10 km deep) are associated with normal faults along the ridge crest and strike-slip movement along transform faults.

Reversals of the magnetic field thus produce spectacular markers of the expansion of the ocean floors. They act as a bar code, imparting a distinctive signature of the age and spreading rate of the ocean floor. These discoveries clearly demonstrate seafloor spreading.

Heat Flow and Gravity

As you might expect for a volcanically active region, large amounts of heat are released from the midoceanic ridge. **Heat flow** is a measure of the amount of heat escaping per second from a given area and is usually measured in watts/m^2. Measurements show that heat flow is 10 times greater near the ridge crests than for average oceanic crust (Figure 19.11C). In addition, the numerous hot springs at active spreading boundaries show that significant heat is also carried out of the crust by convecting pore water. These data imply that a large heat source—basaltic magma—lies beneath the ridge axis. Heat flow diminishes rapidly as one moves away from the spreading center.

Gravity measurements across an oceanic ridge show low values at the crest and higher values on the adjacent flanks. This **gravity anomaly** indicates that materials below the ridge are less dense than materials of the adjacent crust and mantle (Figure 19.11B). Such measurements also suggest that the ridge is nearly in isostatic equilibrium. Consequently, differences in elevation must also reflect differences in



(A) Magnetic anomalies form a symmetrical pattern of highs and lows centered on the ridge crest. The pattern is caused by seafloor spreading and continuing magnetic field reversals.

(B) The gravity values measured over an oceanic ridge are lower than in adjacent areas, indicating that the ridge is underlain by lower-density rocks than the ridge flanks.

(C) Heat flow in the ocean basins peaks at the midocean ridge. Over only 300 km, heat decreases to one-fifth its value at the ridge.

(D) Gravity and heat flow imply that the ridge is high because of the low density of the hot rocks and magma there. The crust (with seismic velocities of 3.7 to 6.8 km/sec) and lithosphere are very thin at the ridge. The layer with velocities of about 6.5 to 6.8 km/sec is interpreted to consist of gabbro. Seismic wave velocities are abnormally low (7.3 km/sec) beneath the ridge, probably because of partial melting. The higher mantle velocities (7.9 to 8.4 km/sec) mark lithospheric mantle.

FIGURE 19.11 **Magnetism, gravity, heat flow, and seismic wave velocities at a midocean ridge** reveal much about the internal structure and origins of oceanic crust.

density or thickness of the underlying lithosphere. The best explanation for the gravity anomaly is that the lithosphere is very thin just below a ridge and that hot asthenosphere with a lower density extends nearly to the surface. Putting together the gravity anomaly and heat flow data, we can construct accurate models of magma chambers and their surrounding environment beneath a midocean ridge (Figure 19.11D).

STRUCTURE AND COMPOSITION OF THE OCEANIC LITHOSPHERE

Oceanic crust is composed of four major layers: (1) deep-marine sediment, (2) pillow basalts, (3) sheeted dikes, and (4) gabbro. Below the crust lies a zone of sheared mantle peridotite.

Although oceanic crust is much more difficult to study than continental crust because it lies deep below the ocean, seismic investigations of the ocean floor enable geologists to understand the internal structure and composition of the oceanic crust. This understanding is greatly enhanced by direct studies of the ocean floor at fracture zones, by field studies of fragments of oceanic crust thrust onto the continents (ophiolites), and by studies of Iceland, an active part of the oceanic ridge.

Seismic Studies

Seismic velocity and reflection studies show that the oceanic crust consists of four major layers. From the top down, these have been designated as layers 1, 2, 3A, and 3B (Figure 19.12).

How do we study the internal structure of the oceanic lithosphere?

Layer 1 averages 0.4 km in thickness and has been extensively sampled by dredging and drilling. Samples show that this layer consists of fine mud that settled through the deep ocean waters. Layer 1 is thinnest near the ridge and thickens on the flanks (Figure 19.2).

Layer 2 ranges from 1 to 2.5 km thick and has P wave velocities that increase from 3.5 km/sec to 6.2 km/sec with increasing depth.

Layer 3 is the main layer of the oceanic crust and is about 5 km thick. This layer is usually subdivided into two units. *Layer 3A* has a seismic velocity of about 6.8 km/sec. The underlying *Layer 3B* has a velocity of about 7.3 km/sec.

Beneath Layer 3 lies a zone where seismic velocities are abruptly higher—about 8 km/sec. This zone is interpreted to be the upper mantle.

It is important to emphasize that the seismic structure represents units defined on variations in only one physical property—seismic wave velocity. Consequently, the boundaries between these seismic layers do not necessarily correspond exactly with the contacts between specific rock types as seen in drill holes or in ophiolites. Nonetheless, the seismic information reveals that the oceanic crust is layered and that the layers are relatively undeformed, unlike continental crust. Moreover, the seismic data provide a framework into which data from other sources can be integrated to form an accurate interpretation of the structure of oceanic crust.

Studies of Ophiolites

Fortunately, numerous fragments of ancient oceanic crust, with its four layers, have been thrust up on the continents. Here, geologists can study the crust's structure and rock types, gaining information needed to interpret the nature and origin of the seismic layers described above. These fragments of ancient oceanic crust are known as **ophiolites** (literally "snake rock") because of some rock's similarity to the color and texture of snakeskin. There are excellent descriptions of more than

What is an ophiolite?

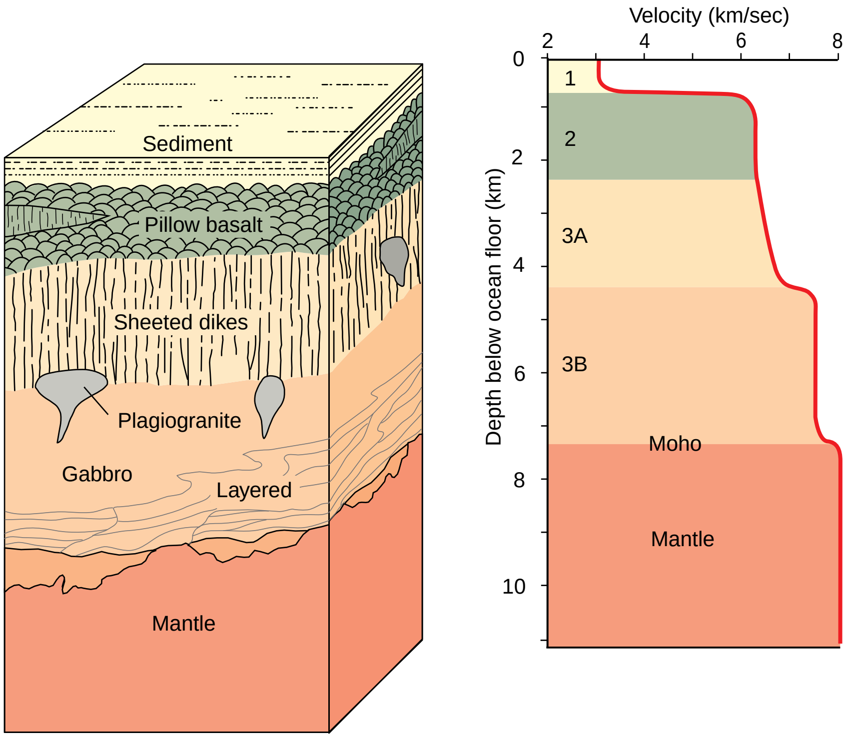


FIGURE 19.12 The major rock units in an ophiolite sequence are shown in this idealized diagram. The uppermost layer consists of deep-marine sediments. Most of the rest of the crust is made of igneous rocks. Pillow basalts and sheeted dikes form thin layers. Massive gabbro underlain by layered gabbro forms the rest of the crust. Peridotites, tectonites deformed in the mantle, are the lowest rocks found in some ophiolites. Ophiolites are thought to be fragments of the ocean floor thrust onto the continents. Correlations with seismically determined layers of the oceanic crust are shown on the right.

100 ophiolites in mountain belts around the world. Most ophiolites were probably accreted onto a continent at a convergent plate margin and now exist as deformed, isolated fragments in folded mountain belts.

One of the most complete ophiolite sequences in the world is in Oman, on the Arabian peninsula off the coast of the Indian Ocean (Figure 19.13). This sequence of rock, as much as 15 km thick, extends about 500 km along the Arabian shore and has a width of 50 to 100 km. The absence of soil and vegetation in the desert climate provides excellent exposures. The Oman ophiolite has remained largely undeformed, unlike others that have been compressed, folded, and faulted. The sequence is only gently folded into broad anticlines. Stream erosion has cut through the slab to expose a complete sequence of oceanic lithosphere from the mantle up through the uppermost oceanic sediments. In studying the Oman ophiolite, we are able to walk across dry ocean floor and climb down into canyons to observe one layer after another in a section through the entire oceanic crust and down into the mantle below.

Careful field studies of the Oman ophiolite, as well as others, lead to the conclusion that the four seismic layers seen in typical oceanic crust can be identified and their origin interpreted. The correspondence between the main units in ophiolite sequences and the seismically determined layers of oceanic crust are shown in Figure 19.12 and described in the following sections.

Sediments. The uppermost layer of the Oman ophiolite sequence consists of a relatively thin layer of deep-marine sediments (Figure 19.14). The thin layers are made of clay and calcareous and siliceous mud derived from shells of microscopic organisms (such as foraminifera, diatoms, and radiolarians). Thin beds of chert are common. Some thin graded beds of sand and mud were deposited by turbidity currents when this piece of oceanic crust was near the continental margin. In most ophiolites, the sediment layer is several hundred meters thick. This layer has been correlated with the sediments found on the ocean floor (Figure 19.12) and with the seismically defined Layer 1.

Basaltic Lavas. Below the sediments, the Oman ophiolite has a thick layer of basalt lava flows with abundant pillows. This extensive mass of pillow basalt is

FIGURE 19.13 The Oman ophiolite is a large sheet of oceanic crust that was thrust onto the Arabian peninsula during its collision with Eurasia. The ophiolite is well exposed and reveals much about the internal structure of oceanic crust.

unlike anything formed on the continents (Figure 19.15) and is evidence that ophiolites originally formed on the ocean floor. More massive sheet flows have columnar joints that developed as the lava cooled. Also common are lava breccias consisting of fragmental debris, formed as the hot lava hit cold seawater. This entire layer ranges from 1.0 to 2.5 km thick. In many places, basalt dikes and sills intrude into the lower part of the lava sequence. This dominantly volcanic layer is most like seismic Layer 2 (Figure 19.12).

Sheeted Dike Complex. Below the pillow basalts, a typical ophiolite has a layer that consists almost entirely of dikes and is known as a **sheeted dike complex.** This distinctive body of rock appears to form much of seismic Layer 3A (Figure 19.12). The individual dikes are vertical tabular sheets a meter or so wide. From a distance, this mass of vertical dikes looks like a sequence of sedimentary strata tilted at a high angle (Figure 19.16). The dikes are igneous intrusions formed by injection of magma into fissures and fractures. The total vertical thickness of this mass of dikes is about 2 km. This is strange geology; for one who has seen only continental sedimentary rocks, the sight of a huge rock mass consisting of nothing but igneous dikes seems unreal.

Another important feature of the sheeted dike complex is the age relationship of the dikes. Each vertical dike is progressively older than the adjacent one. Age does not increase from the top of the body toward its base. At the top of the sheeted dike complex, dikes intrude into the pillow basalt, but the central part of some ophiolites is 100% dikes. The structure of the sheeted dikes has been compared to a deck of cards standing on edge.

How can you recognize a half dike?

Close examination shows how the sheeted dike complex forms. Individual dikes in these swarms are so numerous that they intrude into one another. A dike intrudes along a zone of weakness, which in an area with multiple magma-filled dikes will be either along the margin or in the center of a preexisting dike. This process occurs because an earlier dike may still be hot and therefore weak in the interior, but cold and strong along its margins. Thus, a new fracture develops down the center of a dike, where the rock is weakest. As a result, a new dike splits the older dike in half (Figure 19.17). The final result is the development of dikelike bodies that are in essence **half-dikes** with chilled margins on only one side.

Gabbro. In ophiolites, the sheeted dikes grade downward into a zone of **massive gabbro** (Figure 19.12). The gabbro may be coarse-grained. Below the massive gabbros, the Oman ophiolite is composed mostly of **layered gabbro** and lesser amounts of peridotite.

FIGURE 19.14 Deep-marine sediments at the top of the Oman ophiolite are thin beds of clay and chert. They were originally deposited horizontally but were tilted when the ophiolite sequence was thrust onto continental crust.

FIGURE 19.15 **Pillow basalts** exposed in Wadi Jizzi, Oman, illustrate the characteristics of Layer 2 of the oceanic crust. This rock unit is more than 500 m thick and extends over a vast area in the Oman mountains. The pillows, or sausagelike structures, form as lava is extruded onto the seafloor and chills rapidly in the cold water under high pressure. The outer surface of the pillows is smooth and glassy, the result of rapid quenching of the lava as it contacted cold seawater.

FIGURE 19.16 **Sheeted dikes** exposed in Wadi Hawasina, Oman, are nearly vertical, almost exactly the way they were intruded into the rift zone. Many dikes intrude into earlier dikes, forming half-dikes with chilled borders on only one margin, as shown.

Gabbro represents the main mass of the ophiolite sequence and may be as much as 4.5 km thick. This part of an ophiolite has been correlated with the seismic Layer 3B. The seismic studies show gabbro is just as abundant in oceanic crust as it is in the ophiolite.

The layering and composition suggest that these rocks crystallized from basaltic magma contained in a magma chamber that cooled slowly at shallow depth beneath a midocean ridge. The layers probably formed as crystals accumulated on the walls and floors of the chamber to form distinct layers (Figure 19.18). Layers of chromite (chromium oxide) also form along with the layered gabbros and are among the richest chromium deposits in the world. The layering in these rocks is more regular than in the underlying mantle rocks.

Tectonites (Upper Mantle). The lower part of many ophiolite sequences is made of rocks thought to have formed in the upper mantle (Figures 19.12 and 19.19). These peridotites display a distinctive texture, suggesting ductile deformation at high temperature during seafloor spreading: hence the term **tectonite.** A pronounced lineation or foliation has been produced by the preferred orientation of mineral grains and by concentration of minerals into distinctive layers during deformation. The layers are typically stretched, folded, and refolded, showing that significant flowage occurred during their formation (Figure 19.19B). In many ophiolite sequences, the tectonites are between 5 and 7 km thick, but in some they are as much as 12 km thick. This material was once in the upper mantle, which is rarely exposed at the surface except in ophiolites. The change to high seismic velocities seen at the base of oceanic crust appears to occur in a layer much like the Oman tectonites.

In general, we can make strong correlations between the seismic layers of the oceanic crust and the real compositional layers seen in ophiolites (Figure 19.12). The seismic studies reveal just how far the layered character of oceanic crust extends. Moreover, both ways of studying the oceanic crust show it is very thin (about 6 to 8 km thick) when compared with crust formed at oceanic subduction zones (as much as 20 km thick) or when compared with continental crust (25 to 75 km thick).

The Oceanic Crust Observed by Deep Submersibles

Although ophiolite sequences and seismic studies of the ocean floor reveal much about the composition and structure of oceanic crust, natural cross sections have also been studied directly on the ocean floor in a very few places using submarines. One such area is the Vema Fracture Zone in the central Atlantic, a huge incision in the oceanic crust expressed as a cliff about 3 km high. In 1988 geologists in the French submersible *Nautile* observed and sampled a virtually complete section

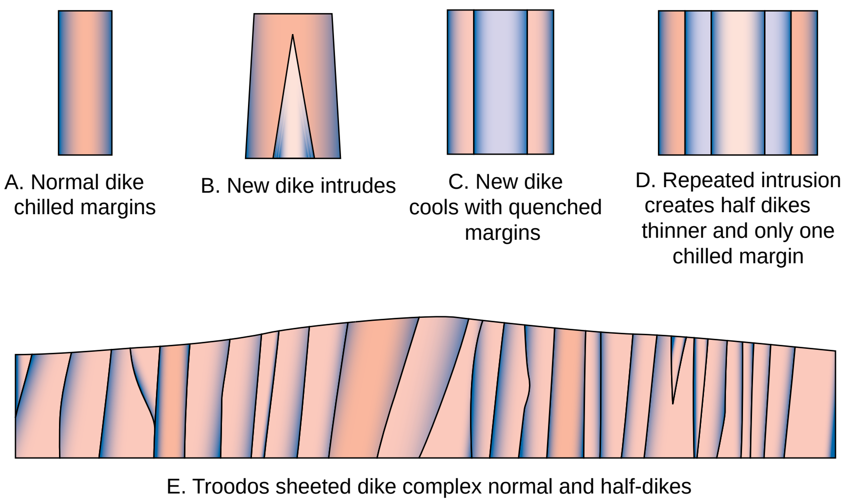


FIGURE 19.17 **Half-dikes** form when a normal dike (A) is split down its hot center by a younger dike (B). The center may be weak because it is still hot and molten. A half-dike (C) has only one chilled margin and is thinner than a normal dike. Repeated intrusion (D) forms a sheeted dike complex above an ocean ridge magma chamber. A representative cross section (E) of the sheeted dike complex in the Troodos ophiolite complex, Cyprus, shows these relationships.

FIGURE 19.18 **Layered gabbro** in the Oman ophiolite appears to have a structure like sedimentary rocks. Early-formed crystals rich in iron and magnesium settle to the base of the magma chamber and accumulate in distinct layers. Some layers are graded, and others show cross-bedding.

through the oceanic crust in the Vema Fracture Zone (Figure 19.20). Their views complement the observations made on land in ophiolites.

At the bottom of the cliff, the *Nautile* crew discovered peridotite from the upper mantle altered to serpentinite during prolonged contact with seawater. (**Serpentinite** is a metamorphic rock made of the hydrated mineral serpentine.) Continuing up the slopes and cliffs of the fracture zone, the *Nautile* traversed a section of gabbro at least 1000 m thick. Above the gabbro, the divers discovered a dike complex 1000 m high, made exclusively of vertical basaltic dikes intruding into each other. The last 800 m to the top of the fracture zone consisted of basaltic lava flows and many pillows.

The sequence of rocks in this seafloor exposure is nearly identical to that found in ophiolites and provides the best visual correlation between ophiolites and modern oceanic crust.

Geologic Studies of Iceland

Iceland is the best example of an oceanic ridge above sea level. Here geologists can examine in detail the surface expression of an active divergent boundary (although it is complicated by an underlying mantle plume). The island is a plateau of basalt, with a fissure-laced rift extending through the center (Figure 19.21). The Mid-Atlantic Ridge rises to the surface in the southwest and is offset toward the east across a diffuse volcanic and earthquake zone. Although some cinder cones and rhyolite calderas have developed, sheets of basalt extruded quietly from fissures are responsible for the largest volume of the island. Small basaltic shield volcanoes are also aligned along the rifts, showing that vertical fractures brought magma to the surface. The youngest rocks are found along the rift, with progressively older basalts occurring toward the east and west coasts (Figure 19.22). Of special importance are innumerable vertical basalt dikes exposed by erosion. The aggregate width of these vertical dikes is about 400 km. Because of the abundant magma in shallow chambers, groundwater is also heated to form geothermal systems and even geysers. Almost all of the faults that cut the island are normal faults. Shallow earthquakes are concentrated in the rift zone. The two halfs of Iceland are separating by about 2 cm/yr.

To understand the nature of volcanism along divergent plate boundaries, let us examine the largest eruption ever recorded by humans, the Laki fissure eruption in 1783 (Figure 19.22B). Although the eruption occurred on land, it gives us important information about the nature and volume of eruptions at midocean ridges.

(A) Perhaps the best exposures of mantle material in the world form the mountains around Muscat, Oman. Because of the high iron content in these mafic rocks, weathering forms a thin layer of iron oxides ("rust") instead of a typical soil profile.

(B) Closeup view of the mantle peridotite in Oman shows a lineation and foliation resulting from plastic flow as the convecting mantle moves under the diverging plates. At the high temperatures found in the mantle, the minerals are stretched and are flattened as they slide past each other. Mineral layers are contorted and twisted as they flow. Geologists map these structures in the field to determine flow patterns in the mantle beneath the ridge.

FIGURE 19.19 Part of the upper mantle is included in some ophiolite complexes.

The eruption was heralded by a series of earthquakes and the opening of several fissures 25 km long. A shallow graben formed between two of the fissures. The eruption began along part of the fissure zone, and after a day of purely explosive activity, lava reached the surface and poured out to form a huge flow that flooded a river valley. In a single day, the front of the lava flow advanced 15 km. The vent was marked by a row of lava fountains throwing red-hot molten basalt tens of meters into the air. Four more cycles of explosive activity switching to lava eruption occurred before the region became quiet again five months later. When the eruption was finished, 560 km^2 of land was buried under as much as 100 m of new lava, more than 100 new spatter and cinder cones had formed, and 12 km^3 of magma had spilled onto Earth's surface.

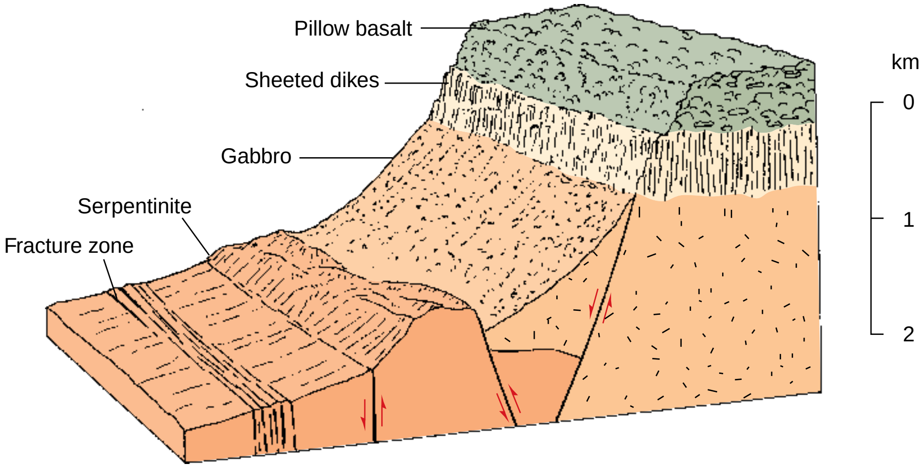


FIGURE 19.20 Geologic section along the Vema Fracture Zone as recorded by the crew of the deep submersible *Nautile* shows a large section of the oceanic crust. Peridotite (altered to serpentinite) makes up the floor of the fracture zone. These are overlain by gabbros, sheeted dikes, and pillow basalts. This is the same sequence of rocks found in ophiolites. *(After A. Nicolas)*

The Laki eruption of 1783 was also a human catastrophe. A blanket of ash and vapors with traces of poisonous sulfur and fluorine were released from the magma. Consequently, about half the island's cattle and three-fourths of its sheep died of starvation or from fluorine poisoning. Because of these secondary effects, more than 20% of the island's human population died of the volcano-induced famine. The influence of the eruption was felt far from Iceland. The winter of 1783–1784 was colder in Europe than usual. Benjamin Franklin, then in Europe, accurately concluded that the fine ash and gases from the eruption had partially blocked the Sun's radiation and caused the cool weather.

Visualizing the Oceanic Crust

The world beneath the sea, where oceanic crust forms, is an alien world completely unlike the surface on dry land. It may be difficult to visualize the geologic processes that occur at oceanic ridges and the nature of the rocks formed there. A significant difference in continental and oceanic environments is the direction in which rocks accumulate. Instead of widespread units of horizontal sedimentary

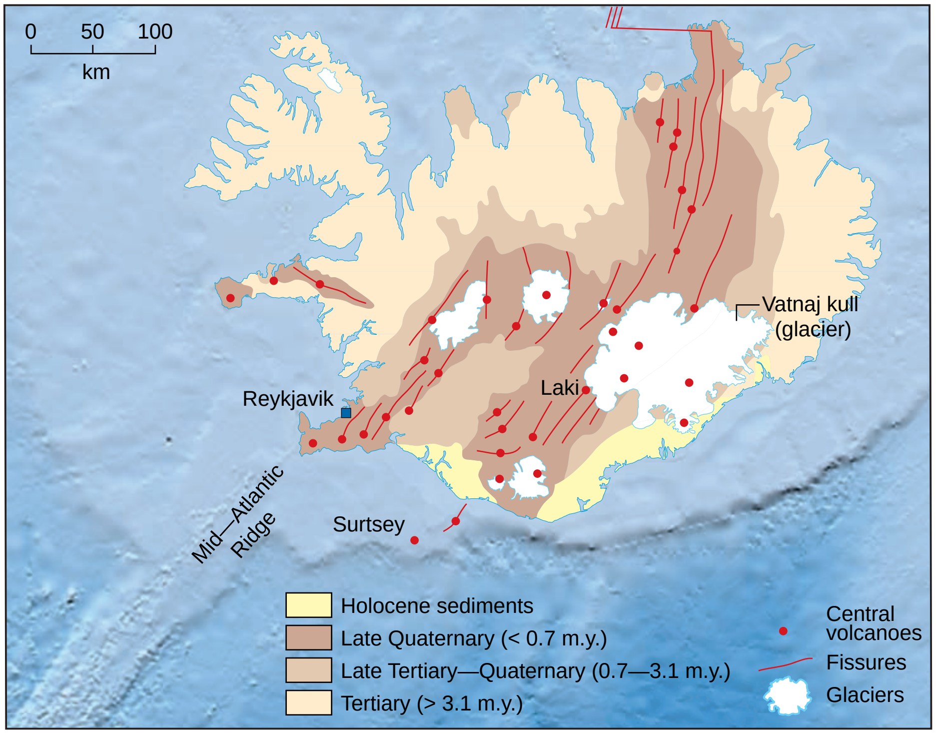


FIGURE 19.21 A geologic map of Iceland shows that the oldest volcanic rocks are along the eastern and western margins and the youngest rocks are near the center of the island. The youngest rocks are basaltic lava flows and dikes that lie in a zone of fissures and active volcanoes. This pattern shows that, as in the rest of the midoceanic ridge, new crust is created here as oceanic lithosphere spreads away from the center of the island.

(A) Old plateau basalts that are highly eroded by glaciers and streams are exposed in east and west Iceland. Here, on the flanks of the rift in eastern Iceland, the basaltic lavas are about 3 million years old.

(B) A fissure eruption at Laki, in Iceland's central rift zone, produced a flood of basaltic lava in 1783. This row of spatter cones marks the fissure vent for this, the largest historic eruption known.

FIGURE 19.22 **Basaltic lava flows** form the bedrock of Iceland. Old lavas are exposed on the flanks of the rift zone and young basaltic flows and other volcanic features are concentrated in the central rift zone. *(Photographs © Yann Arthus-Bertrand/Corbis)*

Why is Iceland so important in understanding the midocean ridges?

strata stacked layer upon layer from vertical accretion, dikes intrude into dikes as they are injected from the chamber below. Thus, crustal accretion in the oceanic realm is lateral and the layers accumulate side by side. The contrast between the sheeted dikes and horizontal sedimentary rocks could not be greater. In a sequence of sedimentary rocks, time lines are nearly horizontal and crustal growth is vertical; in a body of sheeted dikes, time lines are vertical and growth is horizontal (Figure 19.23).

To visualize what the oceanic crust looks like, imagine a section of it compared with the Grand Canyon (Figure 19.24). A sequence of progressively younger horizontal sedimentary layers deposited upon a basement complex of metamorphic rocks is exposed in the real Grand Canyon. If oceanic crust were exposed, we would see thin layers of sediments extending from the canyon rim down to the base of the Coconino Formation. Lavas including pillow basalts would extend to the top of the Precambrian basement. The sheeted dikes would extend another 2000 m below the river. The thick unit of gabbro would extend another 4000 m below this.

ORIGIN AND EVOLUTION OF OCEANIC CRUST

At midocean ridges, basaltic magma forms by decompression melting of rising mantle rock. The magma collects and then begins to crystallize in elongate chambers beneath the ridge. Some magma intrudes upward through dikes and erupts in the rift zone. Seawater is heated as it circulates through the hot crust and causes extensive hydrothermal alteration, metamorphosing large volumes of basalt.

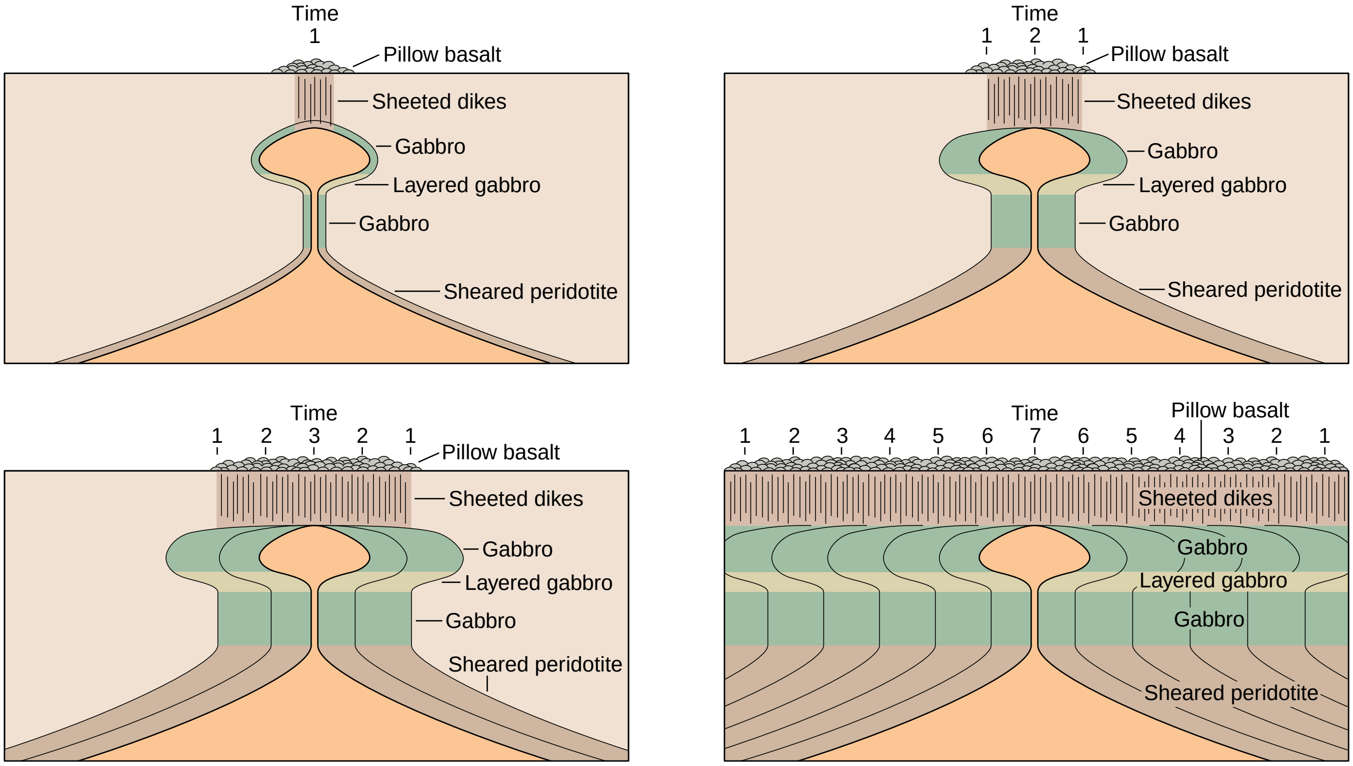


FIGURE 19.23 **Time lines are vertical in oceanic crust,** whereas time lines in continental sedimentary strata, such as those in the Grand Canyon, are horizontal. (Time lines are imaginary lines showing rocks of a given age.) These cross sections show the step-by-step construction of oceanic crust. The horizontal layering of the crust is not the result of simple superposition, but results from spreading during lateral growth of pillow basalts, sheeted dikes, and gabbro.

Magmatism at Oceanic Ridges

Igneous activity is without question one of the most significant processes operating along divergent plate boundaries. Indeed, more igneous rock is formed along ocean ridges than in any other environment in the world. But why is magma generated at divergent plate boundaries rather than at other places? And what processes are involved in creating such large volumes of igneous rock?

The answers lie in what happens to the hot silicate minerals in the mantle as they rise by convection beneath the ridge. The general process is simple. Melting occurs because of a *decrease in pressure,* a process known as **decompression melting** (Figure 19.25). As solid mantle rises beneath a ridge, the pressure gets lower and lower. The mantle peridotite may cool slightly as it rises, but as it reaches shallow depths (about 30 to 100 km) the decrease in pressure causes it to begin to melt. Magma is thus generated beneath the ridges, and not in other places, largely because this is where mantle can rise to a zone of low pressure.

As the peridotite continues to rise, the amount of molten material increases and it becomes like slushy snow—a mixture of solid crystals and newly formed liquid. Eventually, the molten portion accumulates, first into small droplets, then merging into larger and larger teardrop-shaped bodies of magma. The magma, being of lower density, then rises independently of the solid. The melt leaves behind a residue of olivine and pyroxene that becomes sheared to form tectonites (Figure 19.19) attached to the moving lithosphere.Beneath the fast-spreading East Pacific ridge, the zone of partially molten rock may be about 100 km wide.

Much of the rising magma accumulates in a long linear chamber of molten basalt (Figure 19.26) directly below the ridge crest. Seismic studies suggest that the chambers are narrow, only 1 to 5 km across, but chambers as wide as 10 km may exist beneath fast-spreading ridges. The completely molten part is probably only several hundred meters to a kilometer thick. An active magma chamber may not

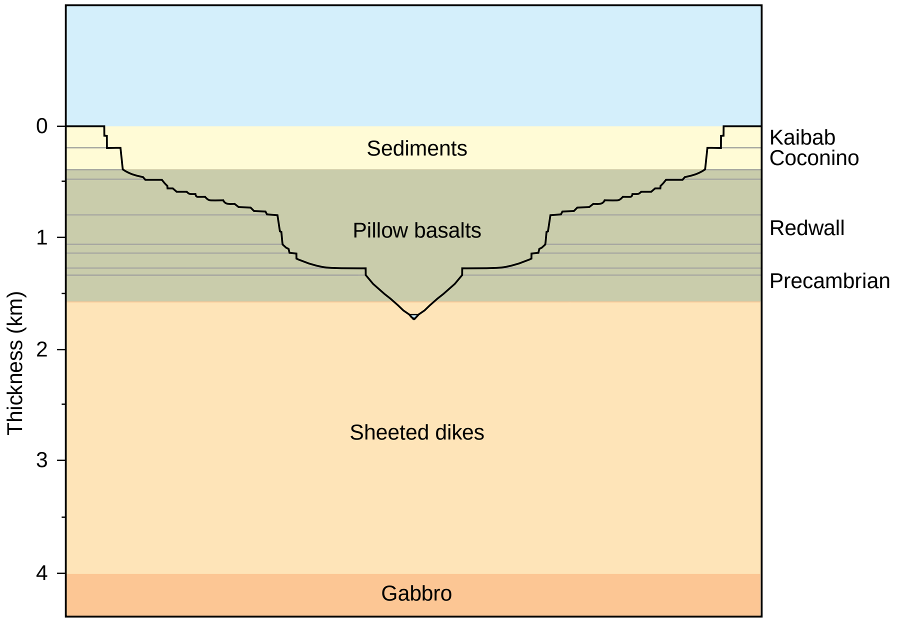


FIGURE 19.24 The oceanic crust compared with a profile of the Grand Canyon shows the magnitude of this sequence of rocks. If the oceanic crust were exposed in the Grand Canyon, the river would flow in the upper part of the sheeted dike complex, which would extend another 2 km below river level. A thick section of gabbros would underlie the entire column.

be present at all times along the entire length of the ridge, especially along those that spread slowly. Periods of magma chamber development and volcanic eruption are interspersed with periods of stretching and faulting.

Because the roof of the axial magma chamber is stretched by plate divergence, vertical dikes grow upward to the floor of the ocean, removing magma from the chamber and forming a sheeted dike complex (Figures 19.16 and 19.26). Magma also erupts to form small shield volcanoes and sheets of fissure-fed lava that build a cover over the sheeted dikes and thicken the crust. Some basalt extruded onto the seafloor is quenched and forms bulbous piles of pillow lava. Most lava flows cool so rapidly in contact with seawater that they move less than 2 km before completely solidifying.

How is magma generated at a mid-oceanic ridge?

Oceanic crust develops as the magma in the axial magma chamber cools and crystallizes to form intrusive rock. The first minerals to crystallize from the basaltic magma are the dense minerals olivine and chromite, which sink to the base of the chamber and form layers (Figures 19.18 and 24.3)—very different from the deformed peridotite of the underlying mantle (Figure 19.19). With further cooling, crystals of pyroxene and plagioclase join olivine and chromite to form layered gabbro. The removal of these minerals from the magma (fractional crystallization) causes the residual melt to change composition. Meanwhile, new batches of magma intrude into the chamber and mix. The upper part of this magma body solidifies to form massive gabbro.

A remarkable characteristic of divergent plate margins is that all of this activity goes on in an extremely small area centered directly on the ridge. The zone where new oceanic crust is formed is only about 10 km wide and 10 km deep. Nevertheless, it extends thousands of kilometers along the midoceanic ridges and is responsible for generation of the entire oceanic crust in little more than 200 million years.

Seafloor Metamorphism

The great expanses of gneiss, schist, and slate exposed in Earth's continental shields dramatically show the effects of metamorphism. Most of these were formed at convergent plate margins in the roots of ancient mountains, where dramatic changes in temperature and pressure were the agents of change. Metamorphism

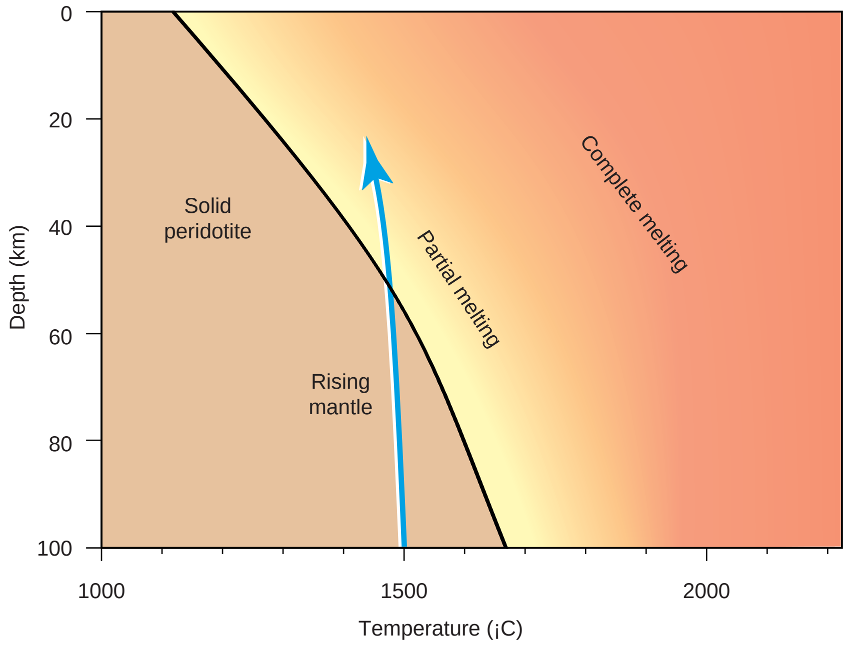


FIGURE 19.25 **Magma forms by decompression melting** under ocean ridges. The black line is the beginning-of-melting curve (the *solidus*) for mantle peridotite. The blue arrow shows the temperature-pressure path followed by mantle that rises directly below the oceanic ridge. When conditions in the upwelling mantle cross the beginning-of-melting curve, basaltic magma is produced. Melting probably occurs between 100 and 30 km deep. The melt can rise upward to form the basaltic crust of the ocean basins.

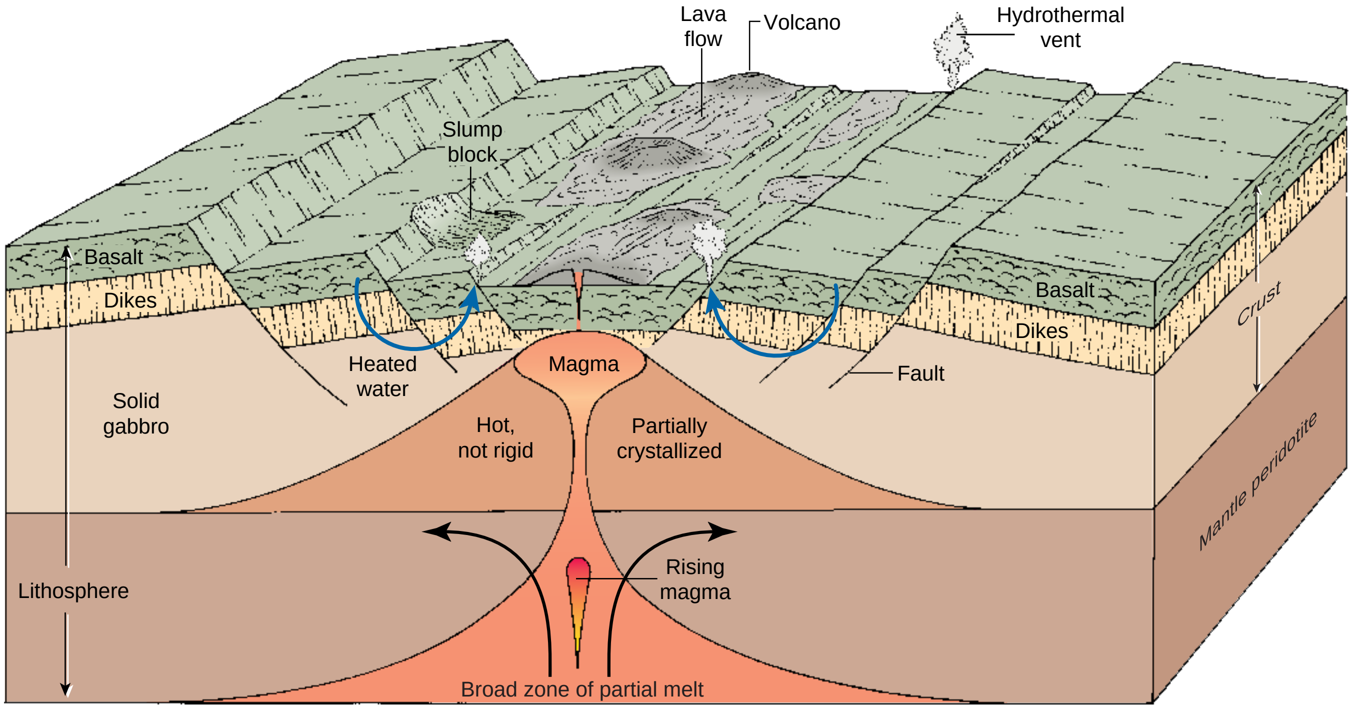


FIGURE 19.26 **An idealized cross section of a midocean ridge** shows that hot mantle rises and then moves laterally. As it rises, pressure decreases and partial melting occurs. The less-dense magma rises buoyantly and collects in a chamber. Heat is lost by conduction and by convection of cold seawater through the hot, permeable crust. The magma consequently cools and crystallizes along the floor and walls of the chamber to form gabbro. As the roof is stretched by plate divergence, sheeted dikes propagate to the surface. The magma erupts to form pillow basalts that add to the roof of the chamber and thicken the crust. Small shields and fissure-fed flows cap the volcanic system. The hydrothermal fluids flow through small vents along the fissure systems to form submarine hot springs that cool as they mix with the surrounding seawater. Sulfides and other minerals dissolved in the fluid crystallize as the fluid cools and changes composition, and mounds of these minerals form.

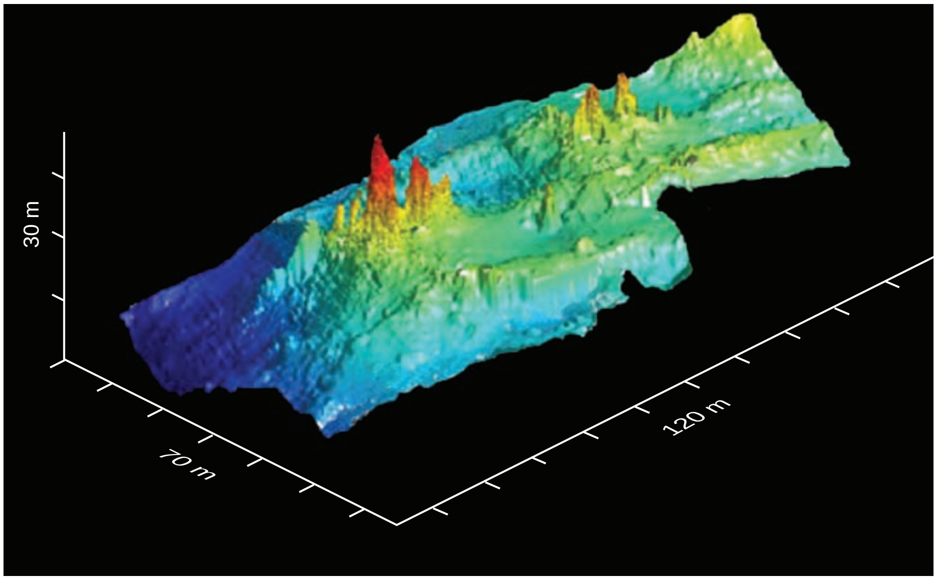


FIGURE 19.27 **Hot springs** form on the seafloor at midocean ridges. Large mounds are created when hot fluids vent from the seafloor and react with cold seawater. This image (above) is of the Endeavour hydrothermal vent field on the Juan de Fuca ridge offshore from the state of Washington. Sulfide minerals precipitate and build up the irregular mounds and complex chimneys. Some chimneys, like this one called *Godzilla* (left), are as tall as skyscrapers. Note the submarine *Alvin,* for scale. *(Courtesy of J. Delaney, V. Robigou, and D. Stakes, 1993. The high–rise hydrothermal vent field, Endeavor Segment, Juan de Fuca Ridge, Geophysical Research Letters, vol. 20, No. 17, p. 1887–1890)*

on the continents is typically accompanied by strong horizontal compression and structural deformation; the metamorphic rocks are folded and foliated.

But there is another type of metamorphism operating at divergent plate boundaries, the results of which we only rarely see on the continents—**seafloor metamorphism.** It is metamorphism in which the *chemical action of fluids* is the major agent of change. Metamorphism along the crest of the midoceanic ridges is caused by the circulation of seawater heated by igneous rocks. At the oceanic ridges, the essential tectonic process is extension that opens narrow fissures. As seawater circulates through the cracks in the hot volcanic rocks, it is heated to 400° to 450°C. This hydrothermal water attempts to equilibrate with the crust and reacts with unstable olivine, pyroxene, and plagioclase to form the new minerals that are stable under these conditions—chlorite, epidote, sodium-rich plagioclase, talc, and serpentine—typical of greenschist facies metamorphism (Figure 6.16 and 6.17). The metamorphic rock is called **metabasalt** and it may be the most abundant kind of metamorphic rock exposed near Earth's surface.

The process that alters the igneous rock along ridge axes, even as they form, is a type of **hydrothermal alteration.** The circulation of hot water through the entire ridge system is a fundamental phenomenon. Lava flows are extremely permeable to the flow of water. Moreover, tectonic stretching and faulting occur at the ridge. Fissures are opened through which seawater can percolate downward, penetrating the crust to depths of 2 to 3 km. Seawater may reach the very base of the dike complex. Deeper penetration of circulating fluids is more difficult owing to the massive nature of the underlying gabbro. Locally, water penetrates deep enough to react with mantle peridotite and hydrate it to form to serpentine. This metamorphic rock is neither dense nor coarsely crystalline; it is a light, weak rock capable of rising isostatically and penetrating the overlying materials like an igneous intrusion.

During the circulation, the hot water not only alters the rock, but it also dissolves minerals from the oceanic crust. Once the water is hot enough, it becomes buoyant, ascends, and is channeled toward central vents on the seafloor.

Some of the dissolved material is precipitated in veins just below the seafloor. The hot water jets through springs and vents on the seafloor to form variously colored mineral-laden plumes several meters high, called **black** or **white smokers.** Copper, zinc, and lead sulfides, as well as other minerals, precipitate from the hot water as it meets the cold oxygen-rich seawater. Chimneylike mounds of minerals up to 10 m high form as these minerals accumulate (Figure 19.9 and Figure 19.27). In fact, many of Earth's important ore deposits formed when seawater reacted with hot volcanic rocks on the ocean floor.

Hydrothermal circulation through the global ridge system is not trivial. The total amount of water circulating through the oceanic crust each year is equivalent to 2% of the annual discharge of all rivers on the planet. Hydrothermal circulation is thus a major element of hydrologic circulation. The system is large enough to recycle the entire volume of the oceans through the oceanic crust every 5 to 10 million years. This circulation has significant effects on the composition of seawater and indirectly on the composition of the atmosphere, which is in equilibrium with the circulating ocean.

Structural Deformation and the Origin of Abyssal Hills

What is the structure of the abyssal hills?

Abyssal hills such as those in Figure 19.5 may seem unspectacular when compared with mountain ranges, island arcs, and deep-sea trenches, but they are singularly important because they form the most abundant landforms on Earth, covering more than 30% of the ocean floor.

New high-resolution topographic data, combined with photography from deep submersibles of abyssal hills in the Pacific, shed new light on their origin. Abyssal hills are long, low ridges typically 10 to 20 km long, 2 to 5 km wide, and 50 to 300 m high (Figure 19.28). They are parallel to the ridge crest. Many hills are asymmetric, with steep slopes facing the ridge axis. The orientation and shape strongly suggest that the basic structures of the hills are normal faults.

Abyssal hills begin to develop when normal faulting is initiated near the crest of the ridge as the plates move away from the axis (Figure 19.28). These faults create short ridges and valleys that are really tilted fault blocks or horsts and grabens. With continued displacement, the faults grow more numerous and longer. Thus, short grabens deepen, widen, and merge with one another even while the plate moves slowly away from the ridge. The abyssal hills are the ridges between the troughs.

Apparently, abyssal hills form near the ridge crest and a short distance down the ridge flank where the crust is extending. Beyond the ridge flank, active faulting and volcanism cease, and the hills become progressively covered with sediment. Near the continents, sediment completely covers the abyssal hills to form the extensive flat **abyssal plains.**

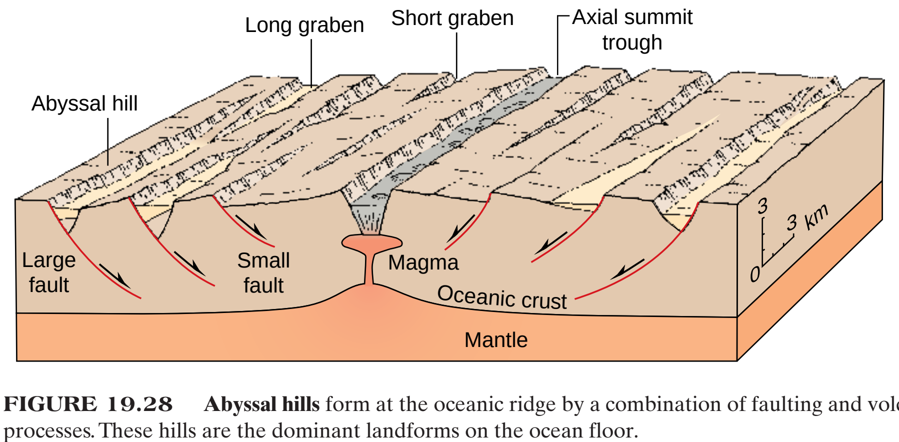


FIGURE 19.28 **Abyssal hills** form at the oceanic ridge by a combination of faulting and volcanic processes. These hills are the dominant landforms on the ocean floor.

Concluding Note

In many ways, studies of midocean ridges represent a remarkable piece of scientific detective work. They give us a clear picture of a part of Earth that is extremely important but obscured and nearly as inaccessible as another planet. It is important to understand the contrasts between oceanic and continental crust thus revealed. First, much of the oceanic crust and its topographic features are related in some way to igneous activity. Moreover, the rocks of the ocean crust have been deformed by extension, not horizontal compression, so their structure contrasts markedly with the complex folds in mountains and shields of the continents. It cannot be overemphasized that the rocks of the ocean crust are all young compared with most continental crust. All oceanic rocks appear to be less than 200 million years old, whereas the great bulk of continental rocks—the ancient rocks of the shields—are more than 700 million years old.

CONTINENTAL RIFTS

Continental rifting occurs when divergent plate margins develop in continents. Continental rifts are typified by thin crust normal faults, shallow earthquakes, and basalt and rhyolite magmatism. Continued rifting creates new continental margins, marked by normal faults and volcanic rocks interlayered with thick sequences of continental sedimentary rocks. As the margin cools and subsides, it is overlain by a thick layer of shallow-marine sediment.

Where are the major divergent plate boundaries on the continents?

Oceanic and continental rifts are quite similar, but they also display significant differences. Continental crust is thicker and less dense than oceanic crust and is structurally much more complex. Continents have a different composition than oceanic crust, being much richer in silica. In addition, rifting of a continent is initiated on dry land, so stream erosion and sedimentation play important roles in the evolution of continental rift zones. Thus, compared to seafloor spreading, continental rifting involves different materials and different events, and it produces its own distinctive structures, landforms, and sequences of rocks.

A **continental rift** is a major elongate depression bounded by normal faults, where the entire lithosphere is deformed. It is a region where the crust has been arched upward, extended, and pulled apart and may develop into a divergent plate margin. The dominant structure is a system of parallel normal faults with large vertical displacements. Faulting produces large elongate down-dropped blocks (grabens or rift valleys) and associated uplifted blocks (horsts). Like their oceanic counterparts, continental rifts are commonly associated with volcanic rocks. The magmas are mostly basaltic, with lesser rhyolite that distinguishes them from oceanic rifts. Lavas of intermediate composition (andesites) are less common than either basalt or rhyolite at most continental rifts.

Continental rifting is not just an academic interest. The **passive continental margins** produced along mature rifts are the largest storehouses of sediment on Earth. As a result, they contain about two-thirds of the world's giant oil fields and hold more than half the world's oil reserves.

What is the dominant structure of the Basin and Range province?

The Basin and Range Province, the East African Rift valleys, the Red Sea Rift, and the margins of the Atlantic Ocean are exceptional examples of continental rifting in various stages of development. From these examples, we can gain important insight into the characteristics of continental rifts and the processes involved in their evolution.

The Basin and Range Province

The Basin and Range Province is a large area of western North America where the crust has been uplifted and pulled apart, forming a complex rift system that

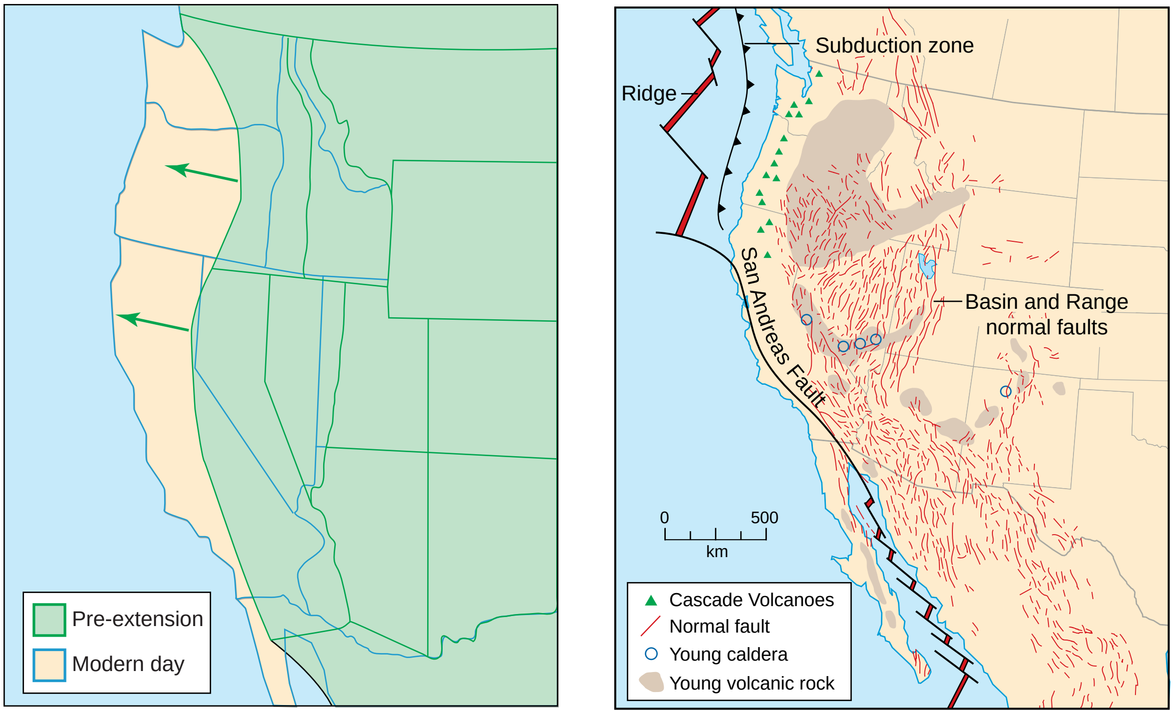


FIGURE 19.29 The Basin and Range Province of western North America extends from Mexico northward into Canada. Partial rifting of the continent has greatly extended the region since about 20 million years ago at a rate of about 1 to 5 cm/yr. Extension created normal faults. The region also has thin crust, high heat flow, and eruptions of basalt and rhyolite.

extends from northern Mexico into Canada (Figure 19.29). Normal faulting, resulting from extension, has produced alternating mountain ranges and intervening fault-bounded basins.

There are more than 150 separate mountain ranges in this province. Some are simple tilted fault blocks with the steeper side of the range marking the side along which faulting occurred. Others are horsts with normal faults on both sides. Estimates of vertical displacement on individual faults are as much as 8 to 10 km. The upthrown blocks may be as much as 3000 m above the valley floors and are considerably dissected by erosion. Earthquakes are common along the eastern and western boundary of the Basin and Range province (Figure 18.6). The total horizontal stretching across the Basin and Range may be more than 300 km.

Structural evidence shows that the Basin and Range is an area where the continental crust has been uplifted and stretched to as much as twice its original width. Geophysical evidence supports this conclusion. Most earthquakes are concentrated along the boundary faults in Nevada and Utah. Heat flow is as much as three times greater than normal. Seismic refraction reveals that the crust is only 25 km thick under much of the region, whereas only 25 million years ago, it may have been as much as 50 km thick. Moreover, the crust overlies a mantle with a low seismic wave velocity. There seems to be no evidence for a high-velocity lithospheric mantle directly below the continental crust. In other words, in this region, the hot asthenosphere may be in contact with the base of the continental crust. Hot springs are a natural manifestation of the high heat flow and thin crust.

Thus, the topography, structure, and geophysical evidence all show that the Basin and Range is undergoing extension that began about 20 million years ago. The overall extension rate is 1 to 5 cm/yr, compared with 2 to 20 cm/yr for mid-ocean ridges.

A distinctive sequence of sedimentary rocks forms in continental rift systems because of faulting of the crust. The sharp local relief created by normal faulting generates vigorous stream erosion. In a dry climate, such as the western United States,

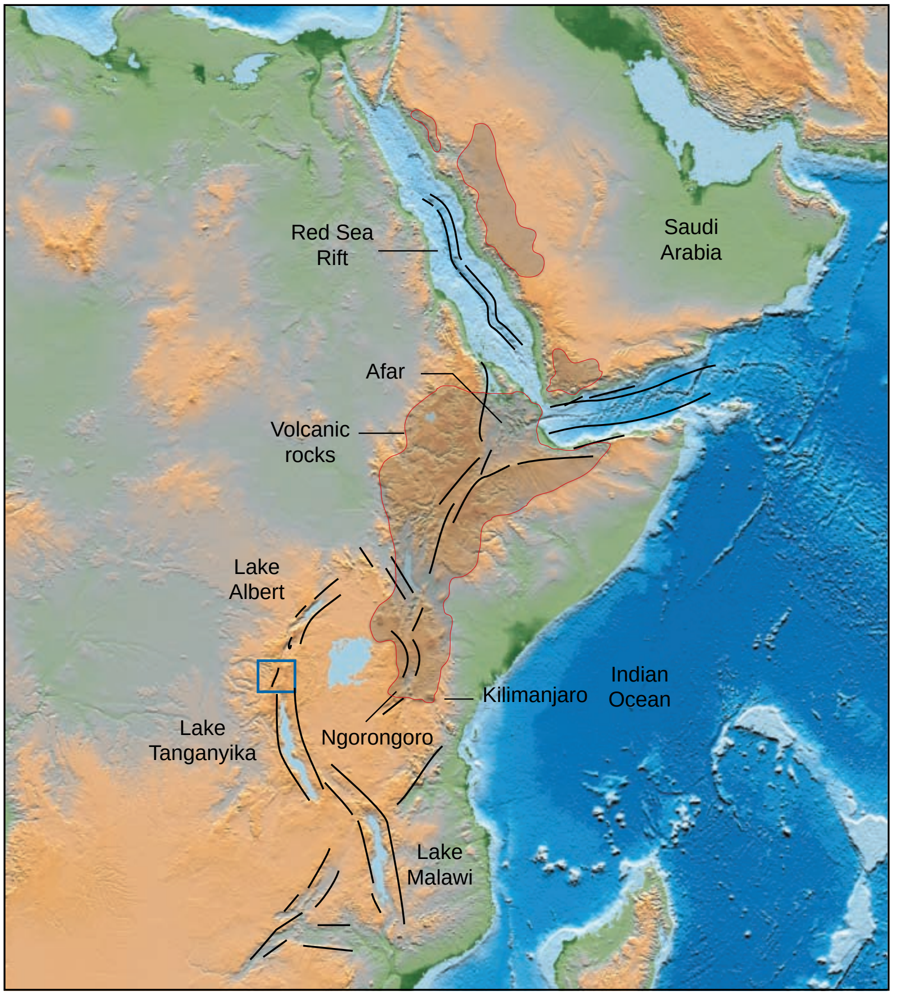


FIGURE 19.30 The East African Rift valleys are where the continent is being uparched and pulled apart. Basaltic volcanism accompanied rifting. If the spreading continues, the rift system may evolve into an elongate sea like the Red Sea to the north. The blue box shows the location of Figure 19.32. *(Courtesy of Ken Perry, Chalk Butte, Inc.)*

thick deposits of sand and gravel accumulate at the base of the mountain ranges as alluvial fans. Large rock avalanche deposits are also common next to the ranges. The sediments of the alluvial fans grade into finer sand and silt and interfinger with lake sediments that accumulate in the lower parts of the basins (see Figure 23.19). In the arid Basin and Range province, the lakes may evaporate to form dry lake beds or playa mud. Thick deposits of gypsum, salt, and other evaporite minerals are commonly formed in the lakes.

Volcanic rocks, mostly basalt and rhyolite, occur both along the Basin and Range margins and near the center. Small flows of basalt are common in these localities. Locally, large calderas formed, caused by repeated eruption of rhyolite ash-flow tuff. Prominent examples include the calderas of southern Nevada and the still-active Long Valley caldera near Mammoth Mountain in eastern California.

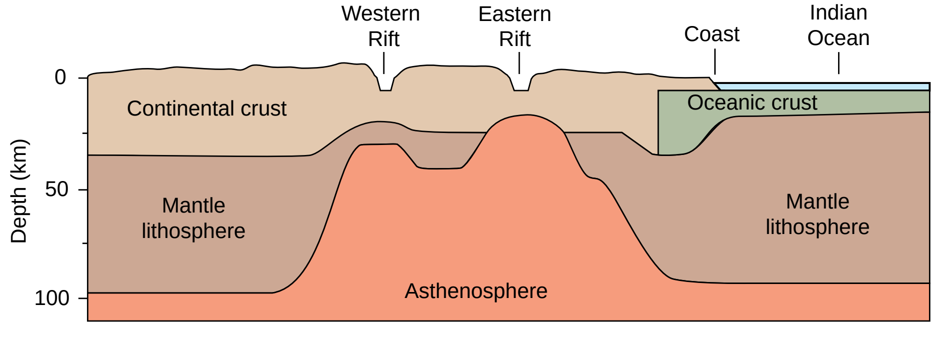


FIGURE 19.31 The thinning of the continental crust beneath the African Rift valleys is indicated by gravity measurements as shown in this cross section. Beneath the valleys, the top of the asthenosphere is near the base of the crust, only 25 km below the surface. The East African Rift valleys represent the first stage of continental rifting.

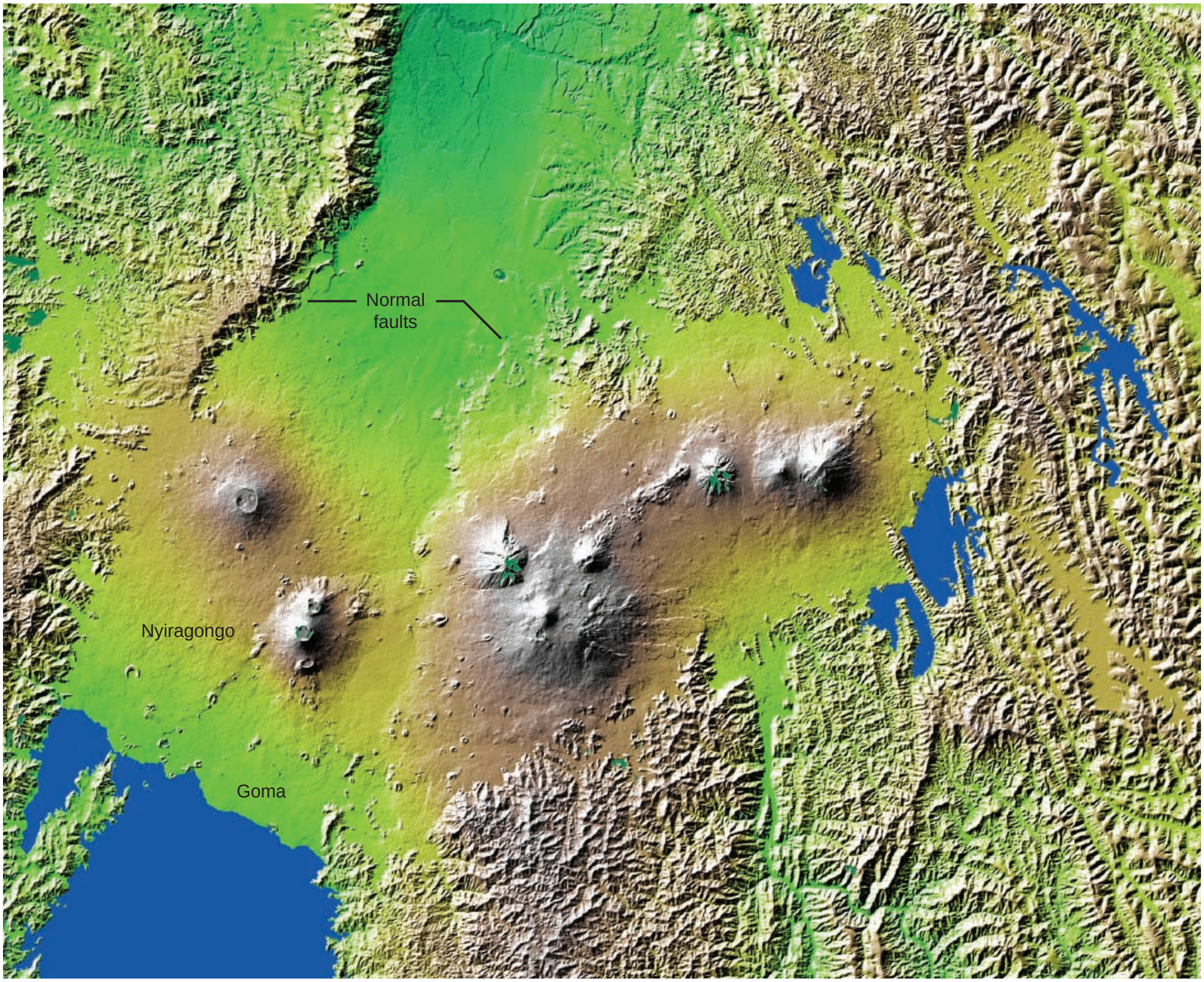


FIGURE 19.32 **The East African Rift** is marked by numerous normal faults, earthquakes, and active volcanoes. This map shows part of the western branch of the rift at the junction of Congo, Rwanda, and Uganda. The main graben is partially filled by Lake Kivu and sediment and lava covered plains. The flanks of the rift are eroded by stream valleys. Large basaltic shield volcanoes and small cinder cones lie on the floor of the rift and on the eastern flank. Some of the volcanoes have large calderas formed by collapse of their summits. In 2002, Nyiragongo erupted fluid lava flows that flooded the town of Goma and displaced 500,000 people. *(Courtesy of NASA/JPL/NIMA)*

The East African Rift

The East African Rift extends from Ethiopia to Mozambique, a distance of nearly 3000 km (Figure 19.30). It consists of a large uparched segment of the crust in which long linear blocks have faulted down near the crest. Many rift valleys are closed depressions and have partly filled with water to form the large freshwater lakes of East Africa. Where evaporation is great, smaller lakes have become saline, forming significant salt deposits.

This part of Africa is underlain by thin crust and thin lithosphere (Figure 19.31). Recent volcanic activity is also associated with the rifting and includes such well-known volcanoes as Mount Kenya, Mount Kilimanjaro, and Nyiragongo (Figure 19.32). Structural and geophysical data show that the region is extending at a rate of about 0.5 cm/yr, with the total extension being slightly less than 50 km. The northern end of the rift, in the Afar region, has a very thin crust (about 8 km). Here, rifting of the continental crust is nearly complete, and basalt volcanoes are abundant.

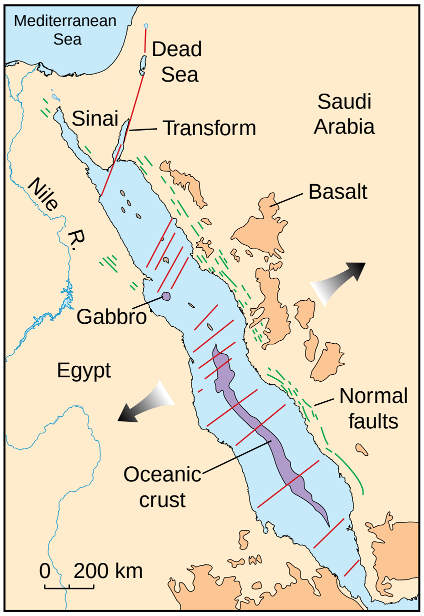


FIGURE 19.33 **The Red Sea** is a narrow ocean basin separating Arabia from Africa. Its margins are steep fault scarps, but much of the Red Sea is floored by thin continental crust. However, a narrow zone of oceanic crust (purple) extends along the Red Sea axis through most of its length. The Red Sea represents the second stage of continental rifting, in which an embryonic ocean develops.

The sequence of rocks generated in the East African Rift valley is similar to that in the Basin and Range. Thick conglomerates and associated alluvial fan deposits occur near the margins of the valleys and grade into stream and lake sediments and evaporites near the center of the basins. Volcanic rocks, including lava flows and ash falls, occur both along the flanks and within the rift valleys. This characteristic rock assemblage stands out in sharp contrast to the sequence of rocks generated at the oceanic ridges, despite both being formed at divergent plate margins.

The Red Sea Rift

The Red Sea, which separates Africa from Arabia, is an important part of Earth's rift system (Figure 19.33). It is an extension of the divergent plate boundary in the Indian Ocean (Figure 19.1). At the northern end of the Red Sea, the rift continues to form the Gulf of Suez, and a major transform fault extends up the Gulf of Aqaba into the Dead Sea and Jordan Valley. The Red Sea Rift is about 3000 km long and 100 to 300 km wide (Figure 19.33). The margins of the Red Sea are steep normal fault scarps, as much as 3 km high, with steplike fault blocks descending abruptly down to the coast.

Much of the Red Sea is floored by continental crust that is thinner than that underlying the flanking land masses. The crust has been thinned by normal faulting and extension (Figure 19.34). Only the south-central part of the Red Sea reaches the abyssal depth of a deep ocean basin and is underlain by oceanic-type crust. Evaporite deposits, mostly salt interbedded with clastic sediments, cover the block-faulted continental shelf with a layer nearly 1 km thick.

Igneous rocks associated with the Red Sea Rift are mostly basalts—dikes, sills, and lava flows associated with fissures parallel to the rift (Figure 19.35). Individual eruptions form small shield volcanoes and cinder cones with associated lava fields. Volcanism and faulting commenced about 25 million years ago.

The small amount of oceanic crust in the deep central part of the Red Sea Rift has a pattern of symmetrical magnetic anomalies typical of the midocean ridge. The magnetic patterns indicate that oceanic crust has been generated for the past 5 million years. The Red Sea is therefore an outstanding example of the initial stages of the formation of an ocean basin: the logical next step from the Basin and Range and East African Rift valleys.

Evolution of Continental Rifts to Passive Margins

On the basis of the examples described above, we can understand the various stages in a progression from a continental rift to a new passive margin (Figure 19.36). The initiating event in continental rifting is believed to be an upwarp or

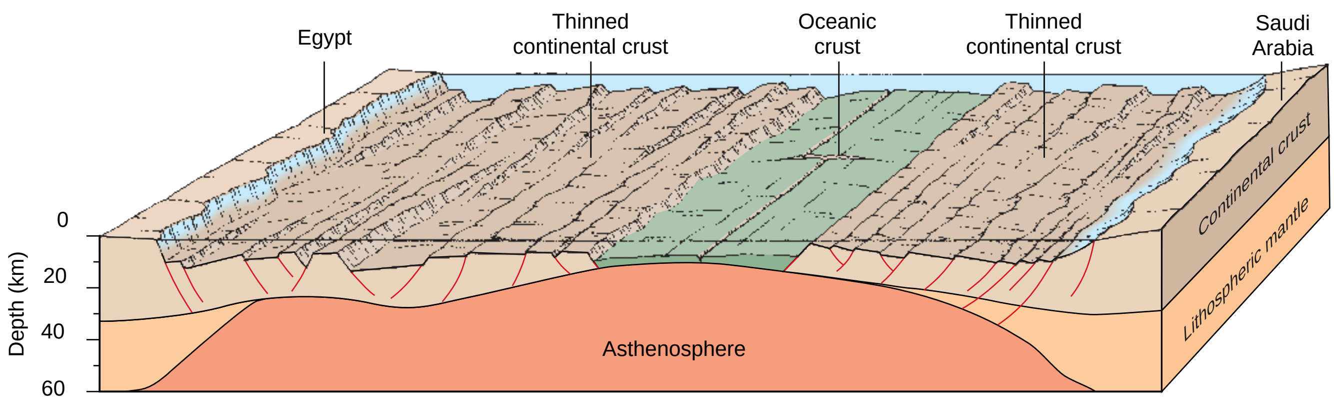
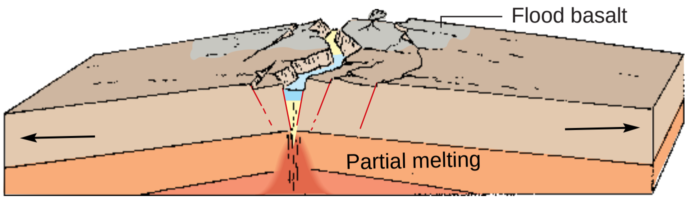
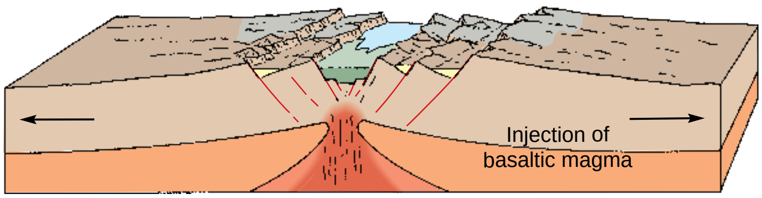


FIGURE 19.34 **A cross section of the Red Sea** illustrates the major structural elements of this stage of rifting. Continental crust is thinned by movement along a series of curved normal faults. The thinned continental crust is overlain by a salt layer up to 1 km thick. New oceanic crust occupies the central part of the rift.

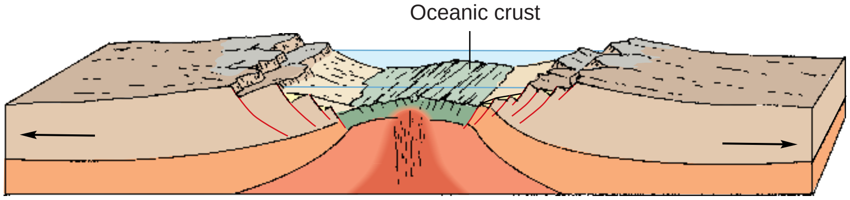
FIGURE 19.35 Swarms of basaltic dikes along the Arabian Peninsula parallel the shore of the Red Sea. They were injected into the continental crust during the early stages of rifting.



(A) Continental rifting begins when the crust is uparched and stretched, so that normal faults (red) develop. Continental sediment (yellow) accumulates in the depressions of the downfaulted blocks, and basaltic magma is injected into the rift system. Flood basalt (gray) can be extruded over large areas of the rift zone during this phase.



(B) Rifting continues, and the continents separate enough for a narrow arm of the ocean to invade the rift zone. The injection of basaltic magma continues and begins to develop new oceanic crust (green).



(C) As the continents separate, new oceanic crust and new lithosphere are formed in the rift zone, and the ocean basin becomes wider. Remnants of continental sediment can be preserved in the down-dropped blocks of the new continental margins.

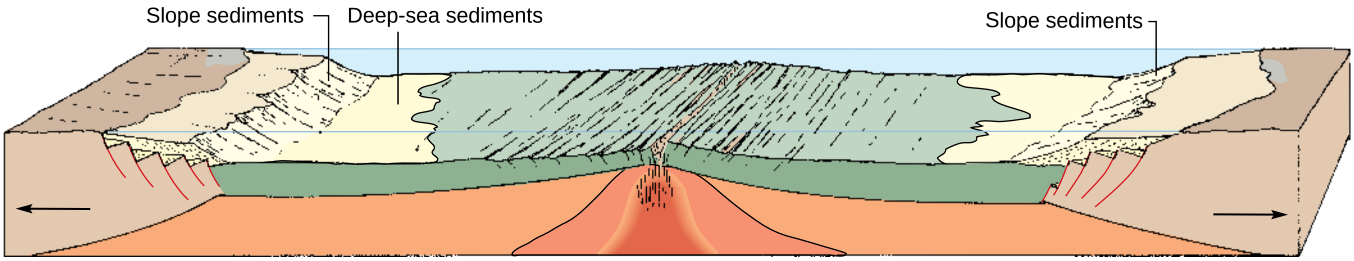


FIGURE 19.36 Stages of continental rifting are shown in this series of diagrams. The major geologic processes at divergent plate boundaries are tensional stress, block faulting, and basaltic volcanism.

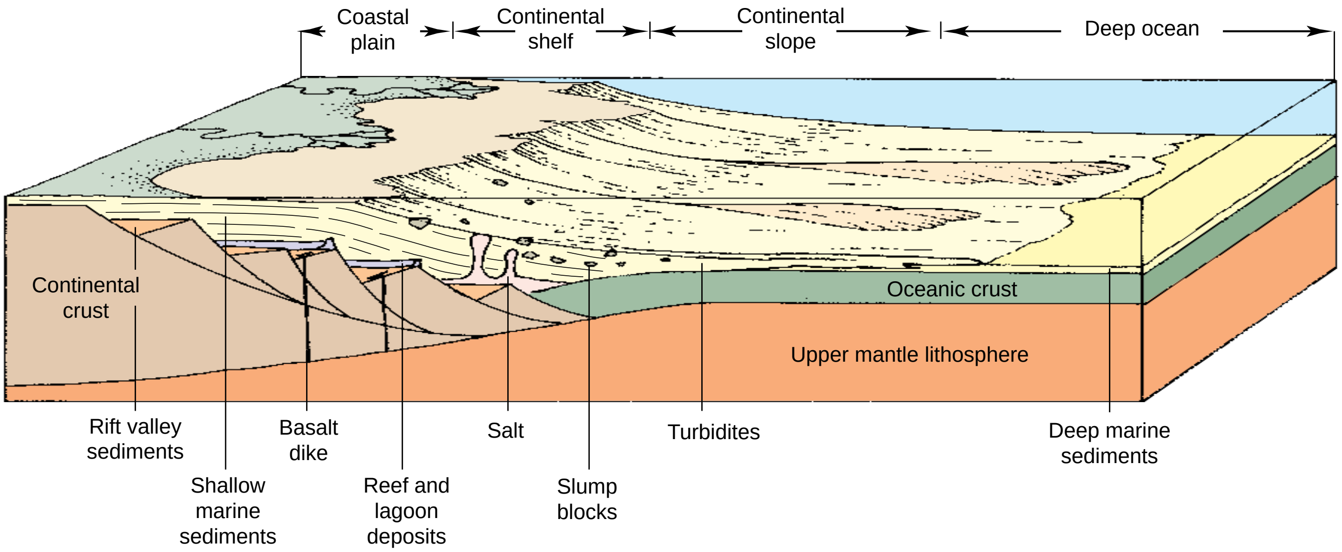


FIGURE 19.37 **A passive continental margin** shows features formed during rifting. Tilted fault blocks that formed during initial rifting define the margins of continental crust. Continental sedimentary deposits consisting of alluvial fan conglomerate and playa lake evaporites may be preserved in narrow grabens. As the continent subsides, reefs and associated beach and lagoon sediments are deposited, and eventually the entire margin is covered by a thick accumulation of shallow-marine sediment that grades into deep-marine sediment. Poorly sorted dirty sandstone and shale are deposited by turbidity currents in the deep water.

dome in a continent. As the lithosphere expands, it arches and thins the crust, fracturing the brittle upper part.

Extension and thinning of the continental crust ultimately create a fault-bounded rift valley. The complexly faulted edges of the rift zone gradually become a new passive continental margin. In an arid climate, the fault blocks erode to form alluvial fans, interlayered with lake deposits. Thick evaporite deposits may accumulate in playa lakes. As the crust thins, the mantle rises and decompression melting may occur. Basaltic eruptions follow. Rhyolitic magma may be produced by partial melting of the granitic crust by heat from the basalt or by differentiation of basaltic magma. These volcanic rocks are interlayered with the sediments within the rift basins.

When the continent moves away from the hot, uparched spreading ridge, the rifted margins begin to subside. Subsidence permits a thick sequence of sediment to accumulate in shallow-oceans at the new passive continental margin. Gradual subsidence of the continental margins occurs for two reasons: (1) As the lithosphere moves off from the hot rising mantle, it cools, contracts, becomes denser, and subsides isostatically; and (2) the weight of the newly deposited sediment on the continental margin causes the crust to be depressed.

With continued subsidence, the oceans ultimately enter the topographic depression to form long, narrow, shallow seas having restricted circulation. Shallow-marine sediments are deposited upon the vestiges of older continental sediments deposited in the original rift valley (Figure 19.37). If the climate is hot and dry, more salt may be deposited atop the graben-filling sediments. Salt deposits formed by evaporating seawater in the embryonic rifts may accumulate to more than 1 km thickness, such as those formed recently in the Red Sea. (The salt may subsequently be mobilized under isostatic pressure and rise as salt domes through the overlying strata.)

Ultimately, the rift widens enough to permit open circulation of marine water. Such narrow seas are commonly fertile ground for marine life. In tropical climates, organic reefs may flourish on the edges of the fault blocks, with associated shallow lagoons and beaches (Figure 19.37). Organic matter accumulates in shallow-marine sediments and may lead to petroleum deposits. As the margin subsides even more, large river systems are refocused to flow toward the shores of the new

STATE OF THE ART
Gravity Variations Reveal Hidden Continental Rift

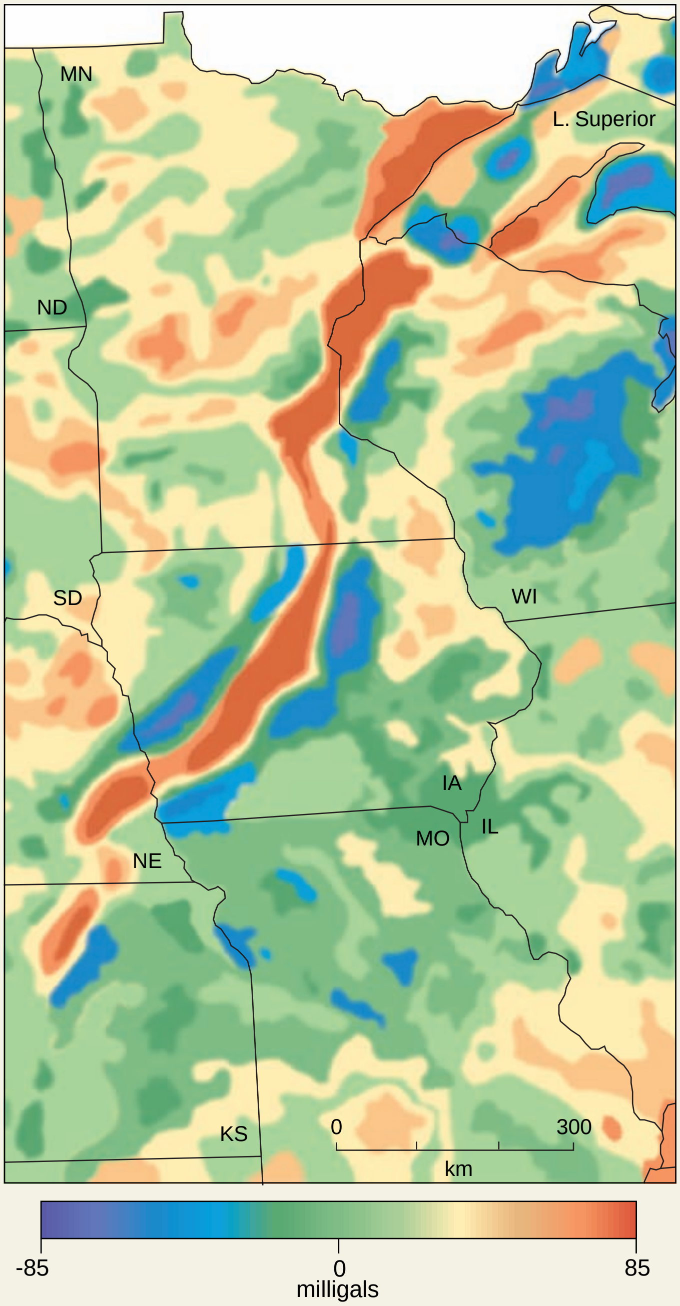
Buried deep beneath the marine limestones and glacial till of Iowa, geologists have found evidence of a giant continental rift that is just over 1 billion years old. Highlighted in red on the map, the rift marks an aborted effort to rip North America apart. The tear is about 100 km wide and 2200 km long. It stretches from northern Kansas across parts of Nebraska, Iowa, Minnesota, Wisconsin and Michigan.

And yet, the *Midcontinent rift* is absolutely invisible through most of its length. For example, a topographic map of central Iowa reveals no elongate trough nor high mountainous flanks, only flat fields of corn and gently rolling hills carved by streams. Even careful geologic mapping shows no normal faults bounding a graben, no basaltic lava flows or intrusive gabbros, no rhyolite ash-flow tuff, no conglomerates or other sediment filling a depression. All these features were long since buried by layers of sedimentary rock that are now several kilometers thick. How then is the map showing this vast rift constructed?

The answer is to use a sensitive instrument called a *gravimeter*. Gravimeters are used to measure small variations in the strength of Earth's gravity. Most gravimeters work by measuring how much a small spring is deformed—the longer the spring stretches, the stronger the gravitational acceleration is at that spot. Like many other geophysical surveys, most gravity surveys are conducted on the ground by making repeated measurements at many different locations. The gravity at each spot on the surface varies by a minute amount from each adjacent spot because of differences in the density of the column of underlying rock. A gravity survey is an indirect way to map density (g/cm^3) variations in the crust. Dense rocks near the surface create a strong gravity field; low-density rocks create a weaker gravity field.

The map of the Midcontinent shown here does not show elevation or the distribution of rock types. The different colors represent the strength of the gravity field measured (in milligals) across the region. A buried continental rift is revealed by a high "ridge" in the gravity field. A long, narrow strip of dense rocks must lie underneath the low-density sedimentary rocks at the surface. Models of the gravity field suggest a fault-bounded trough was filled with dense igneous rocks, such as basalt and gabbro, as much as 7 km thick. In places, these rift rocks are buried beneath a kilometer of sedimentary rock. However, the rift and its dense fill are actually exposed at the surface in Michigan's Keeweenawan peninsula.

Gravity maps like these are very useful for showing the structure of Earth's crust at depth and, as you can see, help us see below deposits of soil, glacial drift, sedimentary rock, or thick vegetation. They can also be used to find faults that otherwise might be undetected—until they rupture in massive earthquakes. Gravity maps are also used in the exploration for ore deposits and petroleum. In fact, following the discovery of the Midcontinent gravity high, the exploration efforts of a few oil companies proved the rift exists beneath central Iowa. Cores and chips brought to the surface from these deep holes were Precambrian rocks—dense basaltic lava flows and gabbro intrusions—formed in the ancient rift. Indeed, what your eyes see at the surface is not always the whole geologic story.



ocean. They bring sediment in large volumes to bury the reefs and their associated sediment under thick layers of clean, well-sorted sand, silt, mud, and limestone.

In the deeper water off the continental margins, the sequence of sediment is distinctly different. It consists of poorly sorted sandstone and shale deposited by turbidity currents (turbidites), submarine slump blocks, and rock debris from submarine landslides. As shown in Figure 19.37, turbidites grade seaward into deep-marine organic oozes that cover the basalts of the oceanic crust.

Eventually, the thinned continental crust drifts even farther away from the rift, and new oceanic crust forms in the rift zone and continues to evolve following the pattern of typical oceanic ridges.

PLATE MOVEMENT DURING THE LAST 200 MILLION YEARS

The considerable amount of data on plate motion enables us to trace the development of divergent plate margins during the last 200 million years of Earth history. A large continental mass (Wegener's Pangaea) rifted apart and large ocean basins formed. Subduction accommodated the growth of new ocean basins.

What will be the most significant changes in the next 50 million years if the present pattern of tectonism continues?

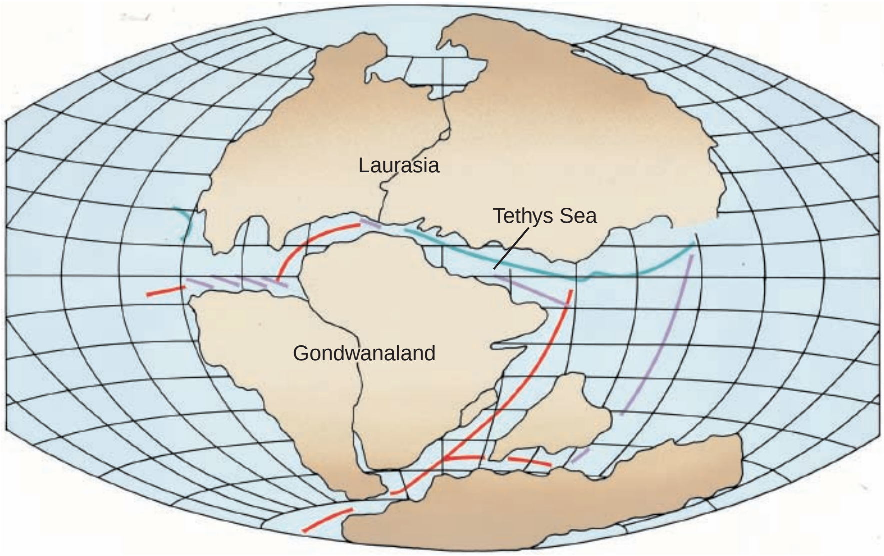
The tectonic system probably has operated during much of Earth's history, and it is responsible for the growth and destruction of ocean basins. Ocean basins come and go because the ancient oceanic crust is consumed at subduction zones and replaced by newer oceanic crust, created at ridges. Continents have rifted apart, drifted with tectonic plates, and rejoined a number of times, but details of the patterns of ancient plate movements are scanty.

Plate Movements

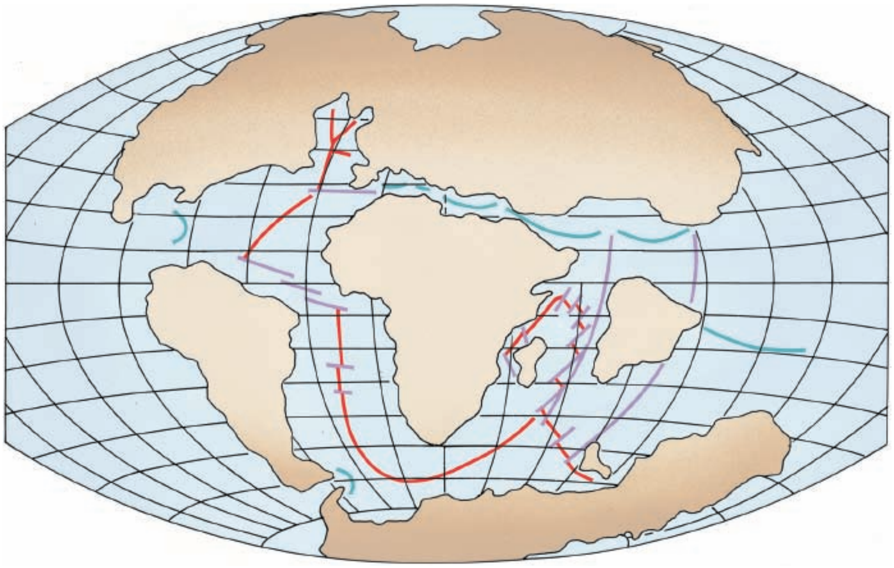
However, the considerable amount of data on plate motion during the last 200 million years enables us to reconstruct the position of continents and to trace plate movement with some certainty (Figure 19.38). They indicate that a large continental mass (Wegener's Pangaea) began to break up and drift apart about 200 million years ago.

The earliest event in the splitting of Pangaea was the extrusion of large volumes of basalt along the initial continental rift zones. Remnants of these basalts are found in the Triassic basins of the eastern United States and the flood basalts of southwestern Africa, western India, and eastern Brazil. A northern rift split Pangaea along an east-west line, slightly north of the equator, and separated the northern continents (Laurasia) from the southern continents (Gondwanaland). A southern rift split South America and Africa away from the rest of Gondwanaland. Soon afterward, India was severed from Antarctica and moved rapidly northward. The plate containing Africa converged toward Eurasia, forming an east-west subduction zone. By the end of the Cretaceous period, 65 million years ago, the South Atlantic Ocean had widened to at least 3000 km. All of the major continents were blocked out by this time, except for the connection between Greenland and Europe and between Australia and Antarctica. A new rift separated Madagascar from Africa, and India continued moving northward.

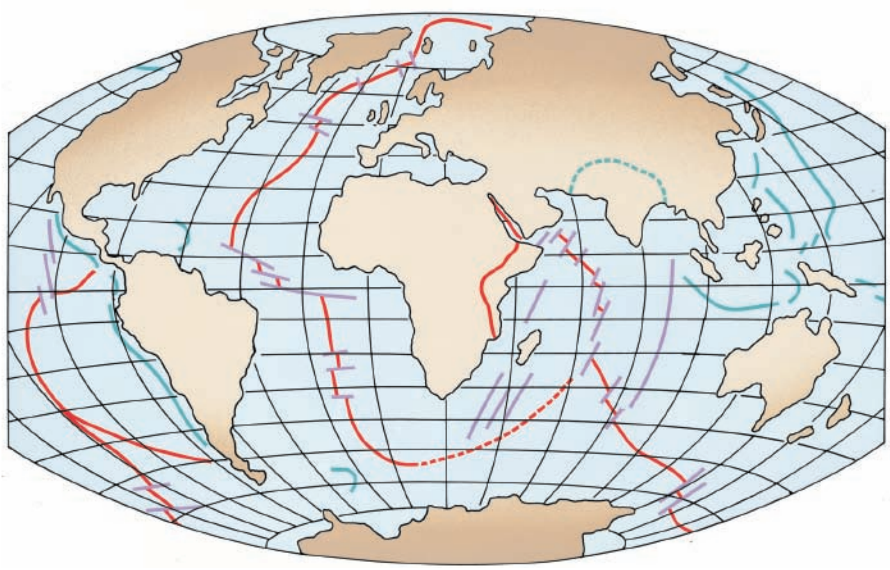
During the last 65 million years, the Mid-Atlantic Ridge extended into the Arctic and finally detached Greenland from Europe. During that time, the two Americas were joined by the Isthmus of Panama, which was created by tectonism and volcanism along the subduction zone. The Indian landmass completed its northward movement and collided with Asia, creating the Himalayas. A new divergent boundary developed as Australia rifted away from Antarctica. Finally, a branch of the Indian rift system split Arabia away from Africa, creating the Gulf of Aden and the Red Sea. Another arm of the rift created the East African rift valleys.



(A) Pangaea, 200 million years ago. Note the Tethys Sea between Laurasia (to the north) and Gondwanaland (to the south).



(B) Plate movement, 100 to 50 million years ago. The Atlantic Ocean is formed as North and South America drift westward. The Tethys Sea is nearly closed.



(C) Plate movement, 50 million years ago to the present.

FIGURE 19.38 The history of plate movement during the last 200 million years has been reconstructed from all available geologic and geophysical data. These maps show the general direction of drift from the time Pangaea began to break up until the continents moved to their present positions.

GeoLogic Sheeted Dikes of the Oman Ophiolite

Geologists trained on the stable platform of a continent are used to seeing vast sheets of nearly horizontal layers of sedimentary rocks stacked one upon another in what has been called layer-cake geology. Imagine the geologic consternation that might possess these same geologists when confronted by this stark desert outcrop of "layers" near Wade Hawasina in Oman.

Observations

1. At first glance, the sheeted dikes resemble a series of deformed, almost vertical, sedimentary beds. But here the "strata" are not layers of sandstone and shale.
2. Instead, they are vertical sheets made of fine-grained plagioclase, pyroxene, and olivine.
3. Most sheets are about a meter thick and have thin borders of very fine-grained rock.
4. More extensive field investigation shows that the sheets grade upward into pillow lavas and downward into gabbro plutons.

Interpretations

The geologic interpretation of these sheets is that each is a solidified dike of basalt that formed below an ancient submarine volcano composed of pillow lavas. The underlying coarse-grained gabbro is an ancient magma chamber from which the basalt in the dikes and flows was extracted. Each dike reveals the stretching and breaking of the oceanic crust at an ancient oceanic ridge. The dikes were filled with new magma freshly extracted from the mantle and added to the growing oceanic crust. The fine-grained margins of the dikes formed when the hot magma quenched against the colder wall rocks. In a way, a dike is like a planar chimney that connects a hot chamber at depth to the surface where hot fluids are extruded.

KEY TERMS

abyssal hill (p. 561)
abyssal plain (p. 561)
black smoker (p. 561)
continental rift (p. 562)
decompression melting (p. 557)
fissures (p. 543)
fracture zone (p. 540)
gravity anomaly (p. 547)
half-dike (p. 550)
heat flow (p. 547)
hydrothermal alteration (p. 560)
layered gabbro (p. 550)
magnetic anomaly (p. 546)
massive gabbro (p. 550)
metabasalt (p. 560)
midocean ridge (p. 538)
ophiolite (p. 548)
passive continental margin (p. 562)
pillow basalt (p. 543)
rift valley (p. 540)
seafloor metamorphism (p. 560)
serpentinite (p. 553)
shallow-focus earthquake (p. 545)
sheeted dike complex (p. 550)
spreading rate (p. 540)
subsidence (p. 542)
tectonite (p. 552)
transform fault (p. 540)
white smoker (p. 561)

REVIEW QUESTIONS

1. What are the major processes that occur at all divergent plate boundaries?
2. Is extension or horizontal compression more common at divergent plate boundaries?
3. Why are divergent plate boundaries in the ocean basins marked by a broad rise?
4. Explain why divergent plate boundaries commonly have shallow earthquakes but lack deep earthquakes.
5. What kinds of volcanic activity are common at divergent plate boundaries?
6. Draw profiles showing the magnetic, gravity, and heat flow anomalies across a typical oceanic ridge. Explain the underlying causes of these anomaly patterns.
7. Compare and contrast a fast- and a slow-spreading ridge, and give examples of each type.
8. What is the significance of the fissure eruptions in Iceland? What structures underlie these fissure-fed lava flows?
9. Describe the typical internal structure of oceanic crust.
10. What is the role of metamorphism in the development of oceanic crust? Describe a typical ocean-floor hydrothermal system.
11. Explain the origin of abyssal hills.
12. How is basaltic magma generated at divergent plate boundaries?
13. Where is rhyolite more common, at an oceanic or a continental rift?
14. Draw a series of cross sections that outline the stages in the development of a continental rift that evolves into an ocean basin.
15. Describe a vertical sequence of sediments and rocks that might be encountered upon drilling into a continental rift basin such as that in East Africa.
16. Why do thick sequences of sedimentary rock accumulate along rifted continental margins?
17. What causes the margins of continental rifts that were once high to eventually subside below sea level?
18. Why are continental rifts developed on high bulges in the crust?
19. Which formed earlier, the North or the South Atlantic ocean?

ADDITIONAL READINGS

Bonatti, E. 1994. The Earth's mantle below the oceans. *Scientific American* **271:** 44–50.

Keary, P., and F. J. Vine. 1990. *Global Tectonics.* Oxford: Blackwell Scientific.

Moores, E. M., and R. J. Twiss. 1995. *Tectonics*. San Francisco: Freeman.

Nicolas, A. 1995. *The Mid-Oceanic Ridges: Mountains Below Sea Level*. Berlin: Springer-Verlag.

MULTIMEDIA TOOLS

Earth's Dynamic Systems Website
The Companion Website at **www.prenhall.com/hamblin** provides you with an on-line study guide and additional resources for each chapter, including:

- On-line Quizzes (Chapter Review, Visualizing Geology, Quick Review, Vocabulary Flash Cards) with instant feedback
- Quantitative Problems
- Critical Thinking Exercises
- Web Resources

Earth's Dynamic Systems CD
Examine the CD that came with your text. It is designed to help you visualize and thus understand the concepts in this chapter. It includes:

- Animations of seafloor spreading
- Movies showing plate motions
- Slide shows with more photos from the Oman ophiolite
- A direct link to the Companion Website