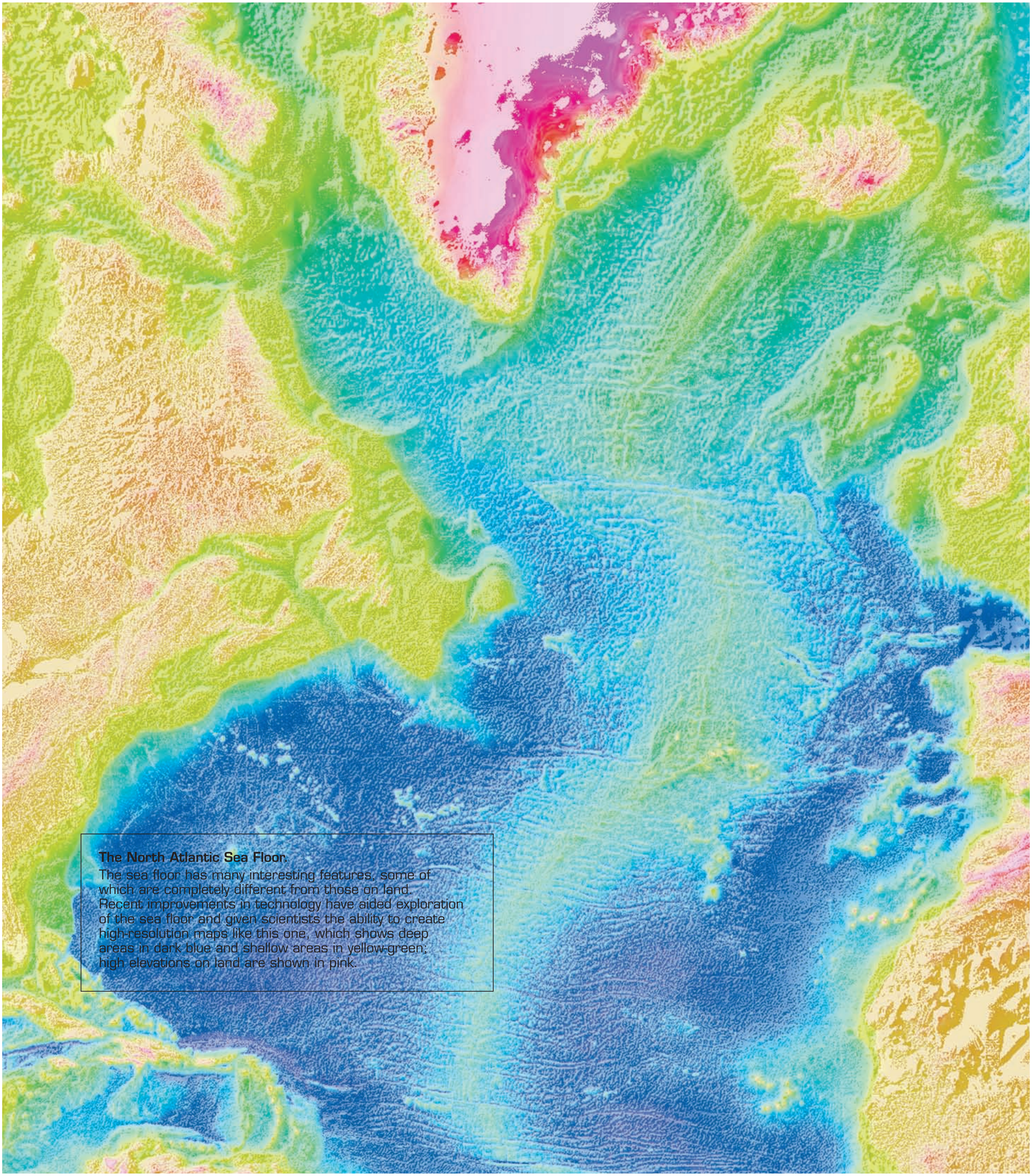

The North Atlantic Sea Floor

The sea floor has many interesting features, some of which are completely different from those on land. Recent improvements in technology have aided exploration of the sea floor and given scientists the ability to create high-resolution maps like this one, which shows deep areas in dark blue and shallow areas in yellow-green; high elevations on land are shown in pink.

> *"Could the waters of the Atlantic be drawn off so as to expose to view this great sea-gash which separates the continents, and extends from the Arctic to the Antarctic, it would present a scene most rugged, grand, and imposing."*
>
> *—Matthew Fontaine Maury (1854), the "father of oceanography," commenting about the Mid-Atlantic Ridge*

3

MARINE PROVINCES

CHAPTER AT A GLANCE

- Echo-sounding from ships is used to determine the shape of the sea floor. More recently, data from satellites are also used to map sea floor features.
- Most continental margins include a shelf, slope, and rise; the deep-ocean floor is dominated by volcanic features and the mid-ocean ridge; ocean trenches are the deepest parts of the sea floor.
- Most ocean floor features are originated by plate tectonic processes.

What does the shape of the ocean floor look like? Over a century and a half ago, most scientists believed that the ocean floor was completely flat and carpeted with a thick layer of muddy sediment containing little of scientific interest. Further, it was believed that the deepest parts were somewhere in the middle of the ocean basins. However, as more and more vessels crisscrossed the seas to map the ocean floor and to lay transoceanic cables, scientists found the terrain of the sea floor was highly varied and included deep troughs, ancient volcanoes, submarine canyons, and great mountain chains. It was unlike anything on land and, as it turns out, some of the deepest parts of the oceans are actually very close to land!

As marine geologists and oceanographers began to analyze the features of the ocean floor, they realized that certain features had profound implications not only for the history of the ocean floor, but also for the history of Earth. How could all these remarkable features have formed, and how can their origin be explained? Over long periods of time, the shape of the ocean basins has changed as continents have ponderously migrated across Earth's surface in response to forces within Earth's interior. The ocean basins as they presently exist reflect the processes of plate tectonics (the topic of the previous chapter), which help explain the origin of sea floor features.

3.1 What Techniques Are Used to Determine Ocean Bathymetry?

Bathymetry (*bathos* = depth, *metry* = measurement) is the measurement of ocean depths and the charting of the shape, or *topography* (*topos* = place, *graphy* = description of) of the ocean floor. Determining bathymetry involves measuring the vertical distance from the ocean surface down to the mountains, valleys, and plains of the sea floor.

Soundings

The first recorded attempt to measure the ocean's depth was conducted in the Mediterranean Sea in about 85 B.C. by a Greek named Posidonius. His mission was to answer an age-old question: How deep is the ocean? Posidonius's crew made a **sounding**[1] by letting out nearly 2 kilometers

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[1] A *sounding* refers to a probe of the environment for scientific observation and was borrowed from atmospheric scientists, who released probes called soundings into the atmosphere. Ironically, the term does not actually refer to sound; the use of sound to measure ocean depths came later.

(1.2 miles) of line before the heavy weight on the end of the line touched bottom. Sounding lines were used for the next 2000 years by voyagers who used them to probe the ocean's depths. The standard unit of ocean depth is the **fathom** (*fathme* = outstretched arms[2]), which is equal to 1.8 meters (6 feet).

The first systematic bathymetric measurements of the oceans were made in 1872 aboard the HMS *Challenger*, during its historic three-and-a-half-year voyage.[3] Every so often, *Challenger*'s crew stopped and measured the depth, along with many other ocean properties. These measurements indicated that the deep-ocean floor was not flat but had significant *relief* (variations in elevation), just as dry land does. However, determining bathymetry by making occasional soundings rarely gives a complete picture of the ocean floor. For instance, imagine trying to determine what the surface features on land look like while flying in a blimp at an altitude of several kilometers on a foggy night, using only a long weighted rope to determine your height above the surface. This is similar to how bathymetric measurements were collected from ships using sounding lines.

Echo Soundings

The presence of mid-ocean undersea mountains had long been known, but recognition of their full extent into a connected worldwide system had to await the invention and use of the **echo sounder**, or *fathometer*, in the early 1900s. An echo sounder sends a sound signal (called a **ping**) from the ship downward into the ocean, where it produces echoes when it bounces off any density difference, such as marine organisms or the ocean floor (Figure 3.1). Water is a good transmitter of sound, so the time it takes for the echoes to return[4] is used to determine the depth and corresponding shape of the ocean floor. In 1925, for example, the German vessel *Meteor* used echo sounding to identify the underwater mountain range running through the center of the South Atlantic Ocean.

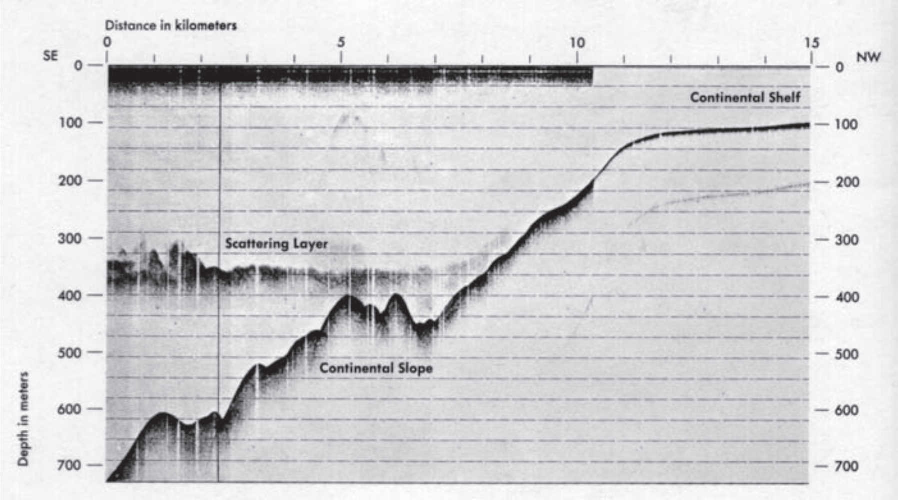

FIGURE 3.1 An echo sounder record. An echo sounder record of the East Coast U.S. offshore region shows the provinces of the sea floor. Vertical exaggeration (the amount of expansion of the vertical scale) is 12 times. The scattering layer probably represents a concentration of marine organisms.

web animation

Sonar and Echolocation

Echo sounding, however, lacks detail and often gives an inaccurate view of the relief of the sea floor. For instance, the sound beam emitted from a ship 4000 meters (13,100 feet) above the ocean floor widens to a diameter of about 4600 meters (15,000 feet) at the bottom. Consequently, the first echoes to return from the bottom are usually from the closest (highest) peak within this broad area. Nonetheless, most of our knowledge of ocean bathymetry has been provided by the echo sounder.

Because sound from echo sounders bounces off any density difference, it was discovered that echo sounders could detect and track submarines. During World War II, antisubmarine warfare inspired many improvements in the technology of "seeing" into the ocean using sound.

During and after World War II, there was great improvement in sonar technology. For example, the **precision depth recorder (PDR)**, which was developed in the 1950s, uses a focused high-frequency sound beam to measure depths to a resolution of about 1 meter (3.3 feet). Throughout the 1960s, PDRs were used

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[2] This term is derived from the method used to bring depth sounding lines back on board a vessel by hand. While hauling in the line, workers counted the number of arm-lengths collected. By measuring the length of the person's outstretched arms, the amount of line taken in could be calculated. Much later, the distance of 1 fathom was standardized to equal exactly 6 feet.

[3] For more information about the accomplishments of the *Challenger* expedition, see Box 5.2.

[4] This technique uses the speed of sound in seawater, which varies with salinity, pressure, and temperature but averages about 1507 meters (4945 feet) per second.

extensively and provided a reasonably good representation of the ocean floor. From thousands of research vessel tracks, the first reliable global maps of sea floor bathymetry were produced. These maps helped confirm the ideas of sea floor spreading and plate tectonics.

Modern *acoustic* (*akouein* = to hear) instruments that use sound to map the sea floor include *multibeam echo sounders* (which use multiple frequencies of sound simultaneously) and side-scan **sonar** (an acronym for *so*und *n*avigation *a*nd *r*anging). **Seabeam**—the first multibeam echo sounder—made it possible for a survey ship to map the features of the ocean floor along a strip up to 60 kilometers (37 miles) wide. Multibeam systems use sound emitters directed away from both sides of a survey ship, with receivers permanently mounted on the ship's hull. Multibeam instruments emit multiple beams of sound waves, which are reflected off the ocean floor. As the sound waves bounce back with different strengths and timing, computers analyze these differences to determine the depth and shape of the sea floor, and whether the bottom is rock, sand, or mud (Figure 3.2). In this way, multibeam surveying provides incredibly detailed imagery of the seabed. Because its beams of sound spread out with depth, multibeam systems have resolution limitations in deep water.

In deep water or where a detailed survey is required, side-scan sonar can provide enhanced views of the sea floor. Side-scan sonar systems such as **Sea MARC** (*Sea Mapping and Remote Characterization*) and **GLORIA** (*Geological Long-Range Inclined Acoustical instrument*) can be towed behind a survey ship to produce a detailed strip map of ocean floor bathymetry (Figure 3.3). To maximize its

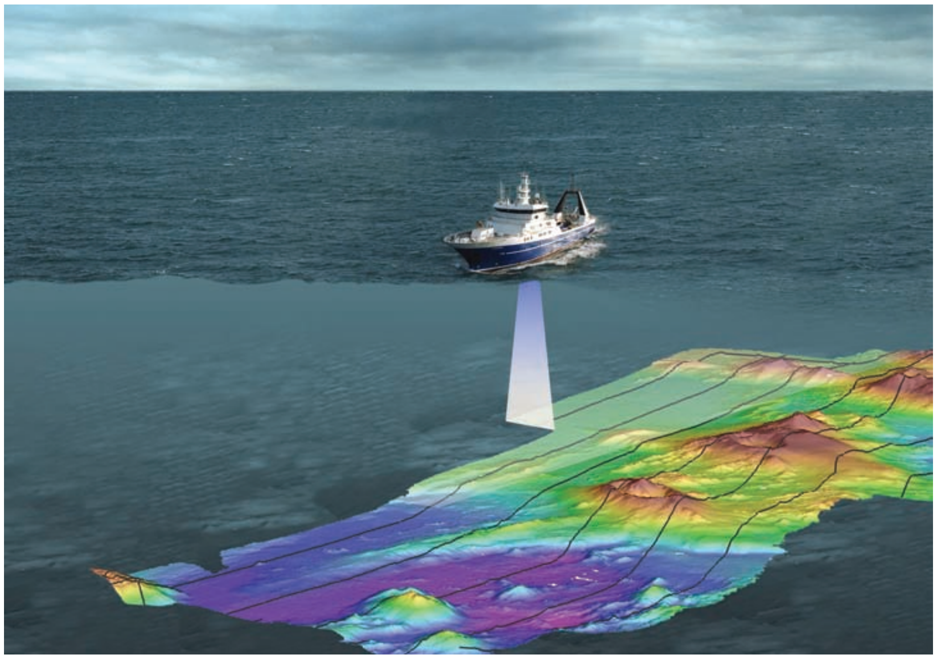


FIGURE 3.2 Multibeam sonar. An artist's depiction of how a survey vessel uses multibeam sonar to map the ocean floor. Hull-mounted multibeam instruments emit multiple beams of sound waves, which are reflected off the ocean floor. Receivers collect data that allow oceanographers to determine the depth, shape, and even composition of the sea floor. As a ship travels back and forth throughout an area, it can produce a detailed image of sea floor bathymetry.

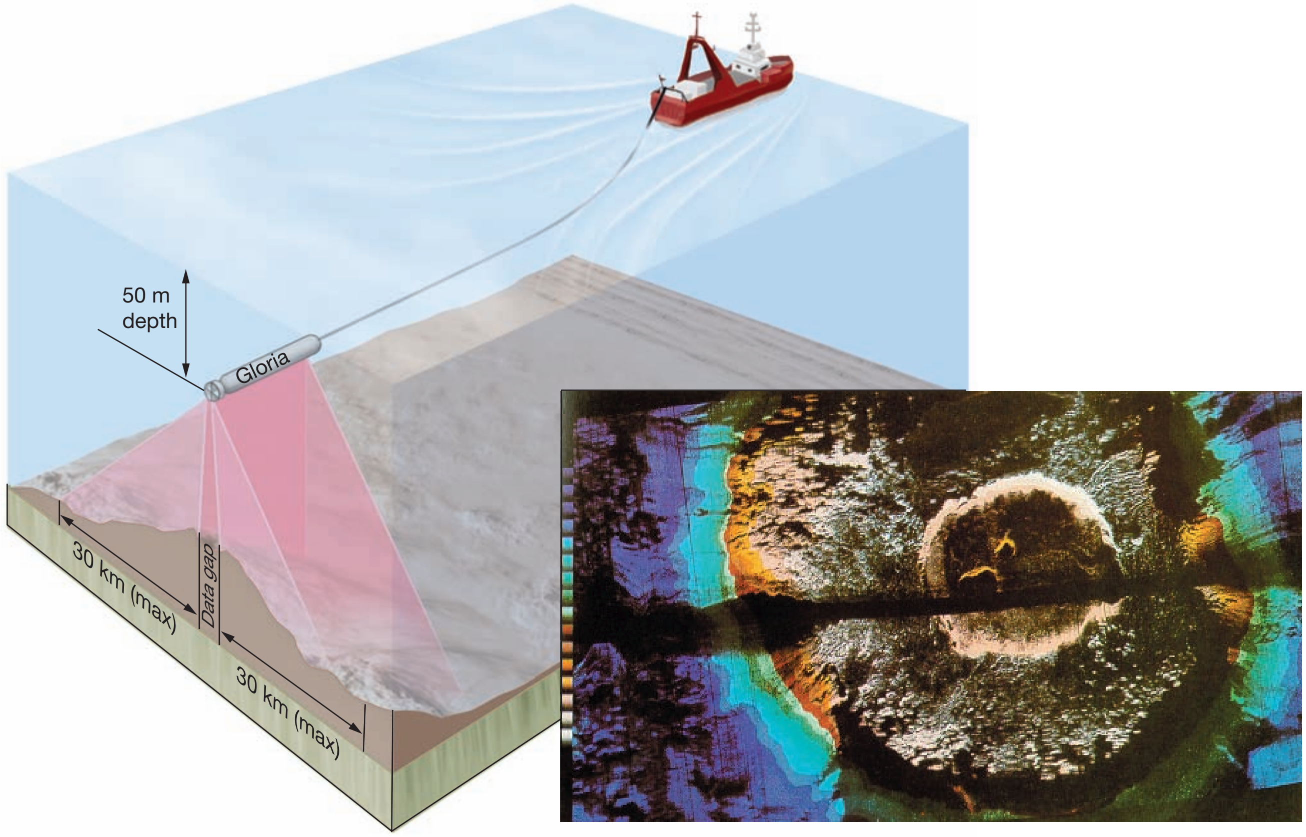


FIGURE 3.3 Side-scanning sonar. The side-scan sonar system GLORIA (*left*) is towed behind a survey ship and can map a strip of ocean floor (a swath) with a gap in data directly below the instrument. Side-scan sonar image of a volcano (*right*) with a summit crater about 2 kilometers (1.2 miles) in diameter in the Pacific Ocean. The black stripe through the middle of the image is the data gap.

3.1 RESEARCH METHODS IN OCEANOGRAPHY

SEA FLOOR MAPPING FROM SPACE

Recently, satellite measurements of the ocean surface have been used to make maps of the sea floor. How does a satellite—which orbits at a great distance above the planet and can view only the ocean's *surface*—obtain a picture of the sea *floor*?

The answer lies in the fact that sea floor features directly influence Earth's gravitational field. Deep areas such as trenches correspond to a lower gravitational attraction, and large undersea objects such as seamounts exert an extra gravitational pull. These differences affect sea level, causing the ocean surface to bulge outward and sink inward mimicking the relief of the ocean floor. A 2000-meter (6500-foot)-high seamount, for example, exerts a small but measurable gravitational pull on the water around it, creating a bulge 2 meters (7 feet) high on the ocean surface. These irregularities are easily detectable by satellites, which use microwave beams to measure sea level to within 4 centimeters (1.5 inches) accuracy. After corrections are made for waves, tides, currents, and atmospheric effects, the resulting pattern of dips and bulges at the ocean

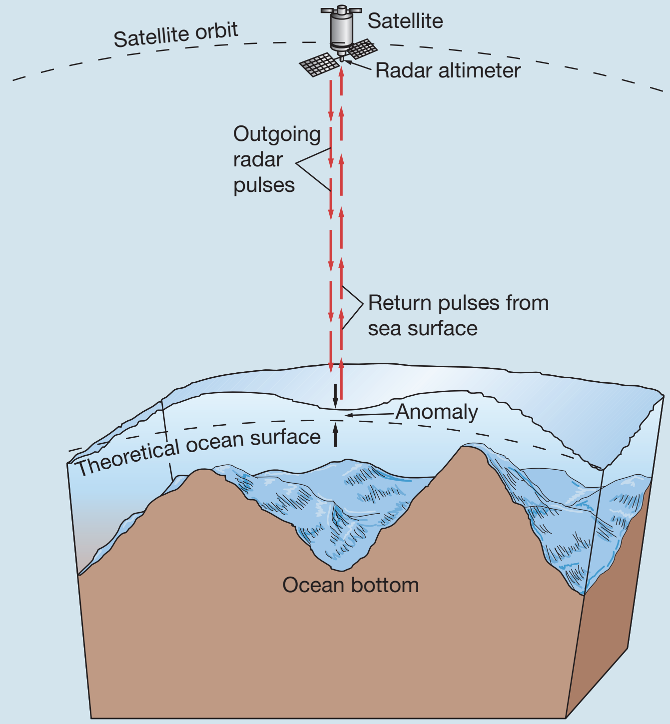


FIGURE 3A Satellite measurements of the ocean surface. A satellite measures the variation of ocean surface elevation, which is caused by gravitational attraction and mimics the shape of the sea floor. The sea surface *anomaly* is the difference between the measured and theoretical ocean surface.

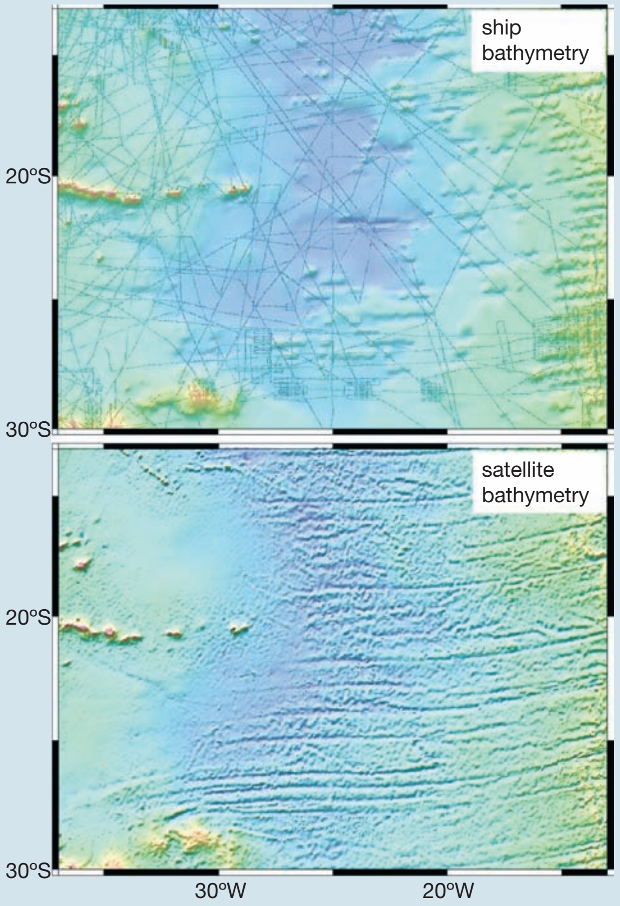


FIGURE 3B Comparing bathymetric maps of the sea floor. Both bathymetric maps show the same portion of the Brazil Basin in the South Atlantic Ocean. *Top:* A map made using conventional echo sounder records from ships (ship tracks shown by thin lines). *Bottom:* A map from satellite data made using measurements of the ocean surface.

WEB VIDEO
The Ocean Floor Seascape

resolution, a side-scan instrument can be towed behind a ship on a cable so that it "flies" just above the ocean floor.

Although multibeam and side-scan sonar produce very detailed bathymetric maps, mapping the sea floor by ship is an expensive and time-consuming process. A research vessel must tediously travel back and forth throughout an area (a process called "mowing the lawn") to produce an accurate map of bathymetric surface can be used to indirectly reveal ocean floor bathymetry (Figure 3A). For example, Figure 3B compares two different maps of the same area: one based on bathymetric data from ships (*top*) and the other based on satellite measurements (*bottom*), which shows much higher resolution of sea floor features.

Data from the European Space Agency's ERS-1 satellite and from Geosat, a U.S. Navy satellite, were collected during the 1980s. When this information was recently declassified, Walter Smith of the National Oceanic and Atmospheric Administration and David Sandwell of Scripps Institution of Oceanography began producing sea floor maps based on the shape of the sea surface. What is unique about these researchers' maps is that they provide a view of Earth similar to being able to drain the oceans and view the ocean floor directly. Their map of ocean surface gravity (Figure 3C) uses depth soundings to calibrate the gravity measurements. Although gravity is not exactly bathymetry, this new map of the ocean floor clearly delineates many ocean floor features, such as the mid-ocean ridge, trenches, seamounts, and nemataths (island chains). In addition, this new mapping technique has revealed sea floor bathymetry in areas where research vessels have not conducted surveys.

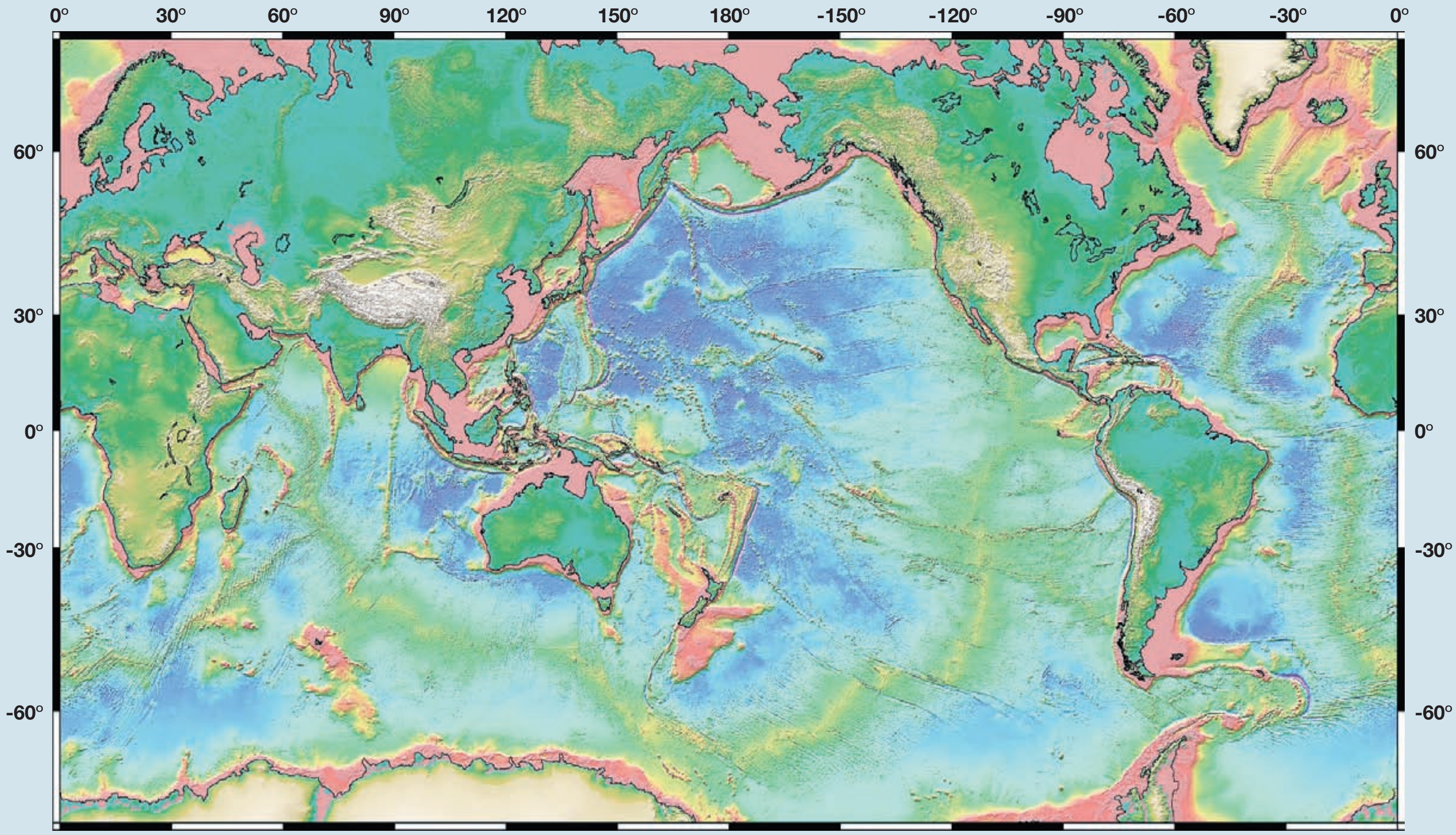


FIGURE 3C Global sea surface elevation map from satellite data. A map showing the satellite-derived global gravity field, which, when adjusted using measured depths, closely corresponds to ocean depth. Purple indicates deep water; the mid-ocean ridge (intermediate water depths) is mostly light green and yellow; pink indicates shallowest water. The map also shows land surface elevations, with dark green color indicating low elevations and white color indicating high elevations.

features (see Figure 3.2). Unfortunately, only a small percentage of the ocean floor has been mapped in this way. An Earth-orbiting satellite, on the other hand, can observe large areas of the ocean at one time. Consequently, satellites are increasingly used to determine ocean properties. Remarkably, technology exists to allow the ocean floor to be mapped by an orbiting satellite (Box 3.1). Recent U.S. oceanographic satellite missions and their objectives are listed in Web Table 3.1.

KEY CONCEPT

Sending pings of sound into the ocean (echo sounding) is a commonly-used technique to determine ocean bathymetry. More recently, satellites are being used to map sea floor features.

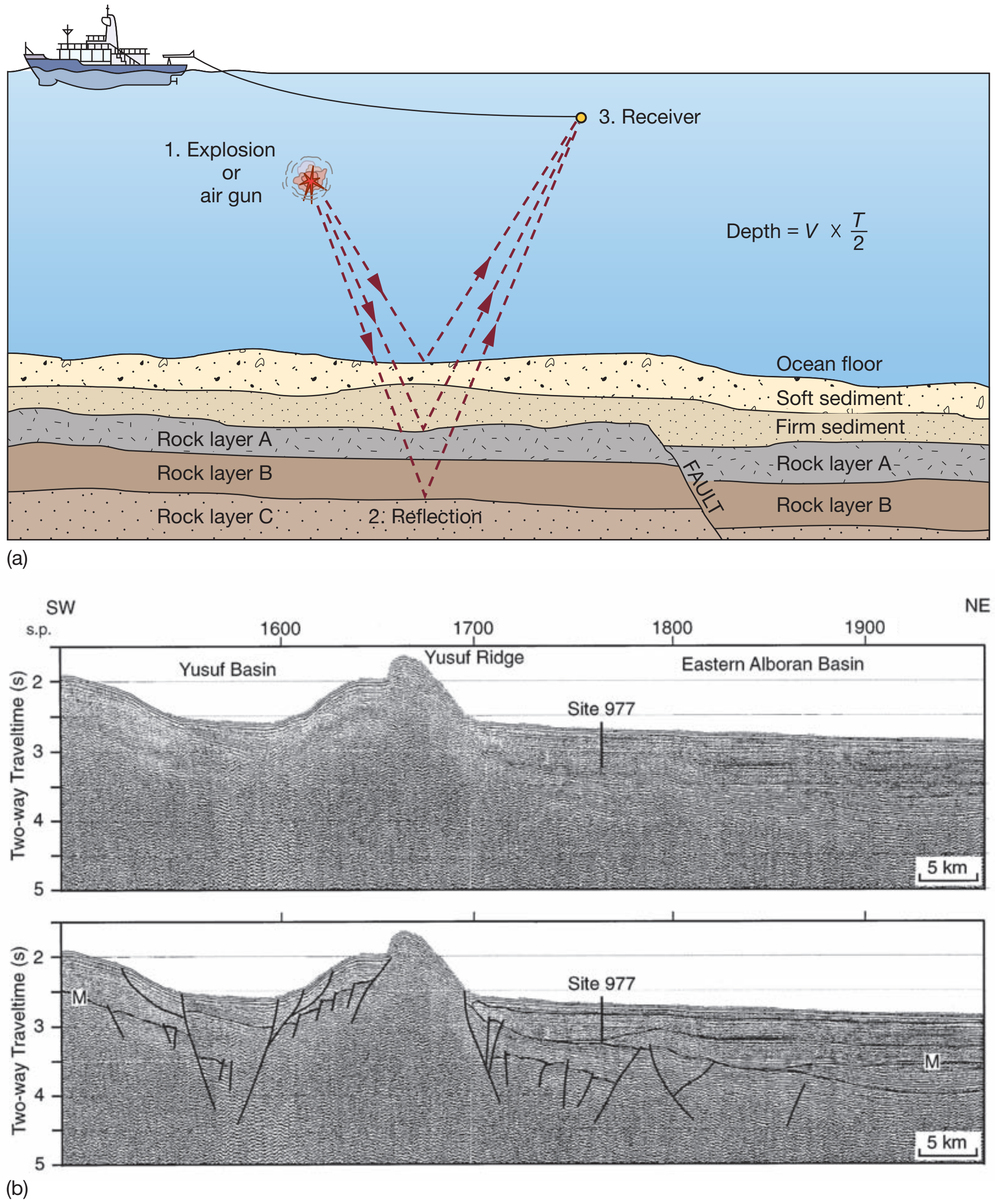


FIGURE 3.4 Seismic profiling. **(a)** An air gun explosion emits low frequency sounds (*1*) that can penetrate bottom sediments and rock layers. The sound reflects off the boundaries between these layers (*2*) and returns to the receiver (*3*). **(b)** *Top*: Seismic reflection profile of the western Mediterranean, showing the location of *JOIDES Resolution* Drill Site 977. *Bottom*: An interpretation of the same seismic profile showing faults (*black lines*). M = M-reflector, which was created during the drying up of the Mediterranean Sea approximately 5.5 million years ago.

Seismic Reflection Profiles

Oceanographers who want to know about ocean structure beneath the sea floor use strong low-frequency sounds produced by explosions or air guns, as shown in Figure 3.4. These sounds penetrate beneath the sea floor and reflect off the boundaries between different rock or sediment layers, producing **seismic reflection profiles**, which have applications in mineral and petroleum exploration.

3.2 What Does Earth's Hypsographic Curve Reveal?

Figure 3.5 illustrates Earth's **hypsographic** (*hypos* = height, *graphic* = drawn) **curve**, which shows the relationship between the height of the land and the depth of the oceans. The bar graph (Figure 3.5, *left side*) gives the percentage of Earth's surface area at various ranges of elevation and depth. The cumulative curve (Figure 3.5, *right side*) gives the percentage of surface area from the highest peaks to the deepest depths of the oceans. Together, they show that 70.8% of Earth's surface is covered by oceans and that the average depth of the ocean is 3729 meters (12,234 feet) while the average height of the land is only 840 meters (2756 feet). The difference, recalling our discussion of isostasy in Chapter 1, results from the greater density and lesser thickness of oceanic crust as compared to continental crust.

The cumulative hypsographic curve (Figure 3.5, *right side*) shows five differently sloped segments. On land, the first steep segment of the curve represents tall mountains, while the gentle slope represents low coastal plains (and continues just offshore, representing the shallow parts of the continental margin). The first slope below sea level represents steep areas of the continental margins and also includes the mountainous mid-ocean ridge. Further offshore, the longest, flattest part of the whole curve represents the deep-ocean basins, followed by the last steep part, which represents ocean trenches.

The shape of the hypsographic curve can be used to support the existence of plate tectonics on Earth. Specifically, the two flat areas and three sloped areas of the curve show that there is a very uneven distribution of area at different depths and elevations. If there were no active mechanism involved in creating such features on Earth, the bar graph portions would all be about the same length and the cumulative curve would be a straight line. Instead, the variations in the curve suggest that plate tectonics is actively working to modify Earth's surface. The flat portions of the curve represent various intraplate elevations both on land and underwater while the slopes of the curve represent mountains, continental slopes, the mid-ocean ridge, and deep-ocean trenches, all of which are created by plate tectonic processes. Interestingly, hypsographic curves constructed for other planets and moons using satellite data have been used to determine if plate tectonics is actively modifying the surface of these worlds.

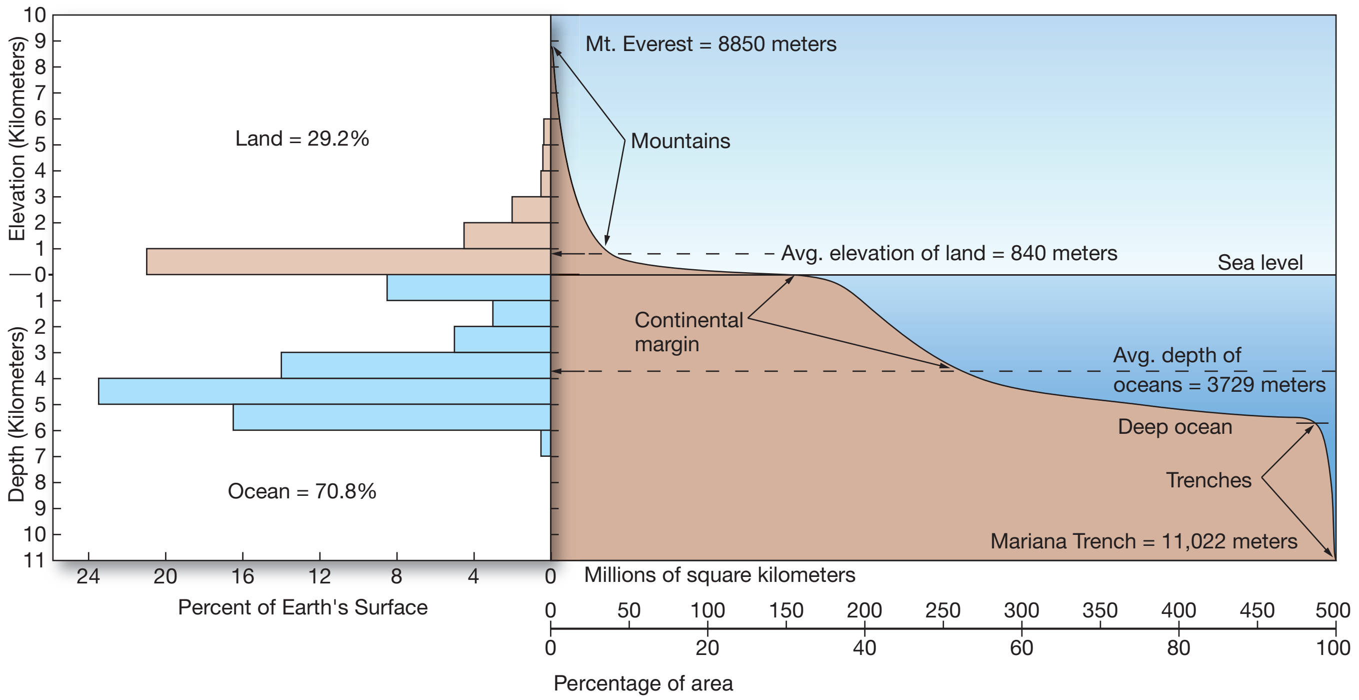


FIGURE 3.5 Earth's hypsographic curve. The bar graph (*left*) gives the percentage of Earth's surface area at various ranges of elevation and depth. The cumulative hypsographic curve (*right*) gives the percentage of surface area from the highest peaks to the deepest depths of the oceans. Also shown are the average ocean depth and land elevation.

3.3 What Features Exist on Continental Margins?

The ocean floor can be divided into three major provinces (Figure 3.6): (1) **continental margins**, which are shallow-water areas close to continents, (2) **deep-ocean basins**, which are deep-water areas farther from land, and (3) the **mid-ocean ridge**, which is composed of shallower areas near the middle of an

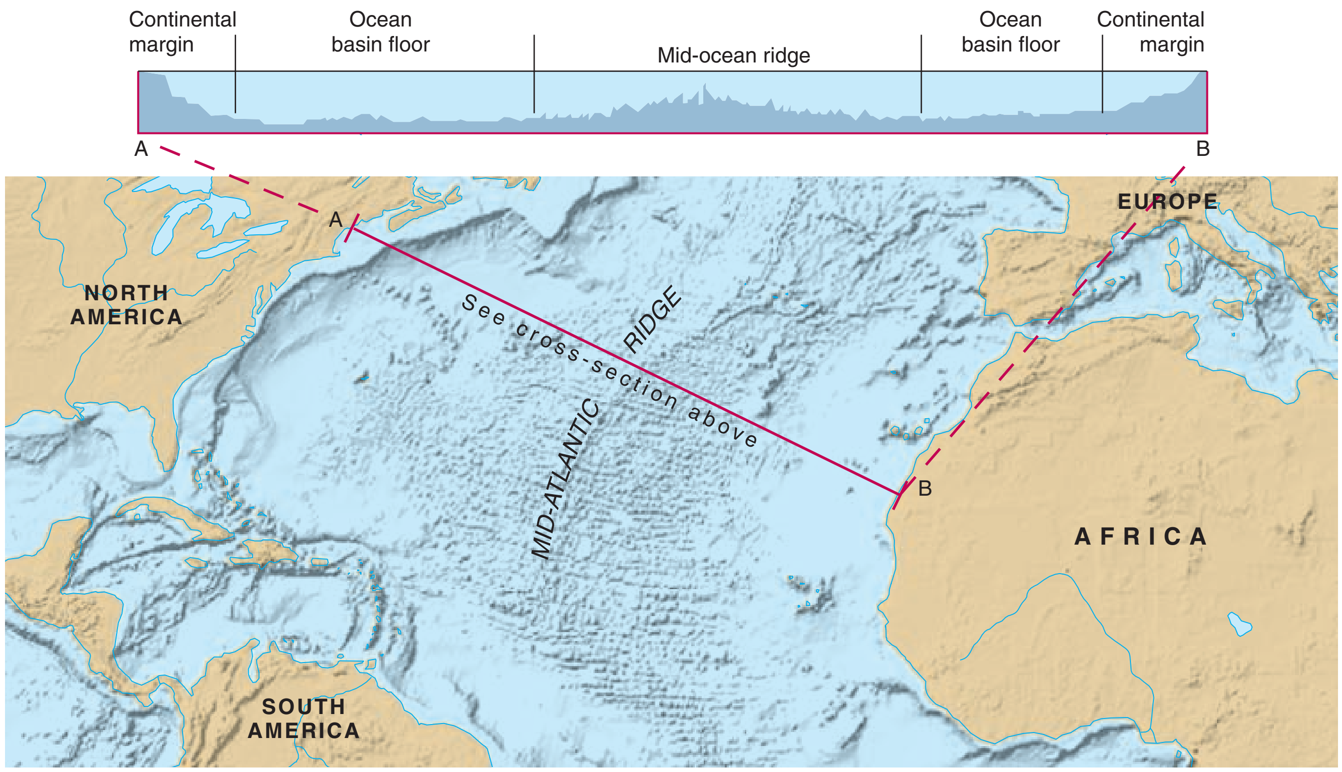


FIGURE 3.6 Major regions of the North Atlantic Ocean floor. Map view below and profile view above, showing that the ocean floor can be divided into three major provinces: continental margins, deep-ocean basins, and the mid-ocean ridge.

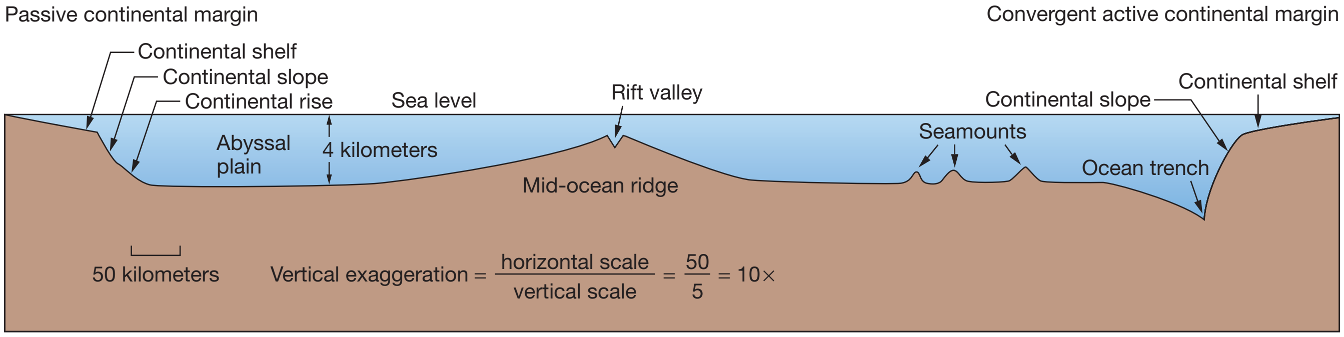


FIGURE 3.7 Passive and active continental margins. Cross-sectional view of typical features across an ocean basin, including a passive continental margin (*left*) and a convergent active continental margin (*right*). Vertical exaggeration is 10 times.

ocean. Plate tectonic processes (discussed in the previous chapters) are integral to the formation of these provinces. Through the process of sea floor spreading, mid-ocean ridges and deep-ocean basins are created. Elsewhere, as a continent is split apart, new continental margins are formed.

Passive Versus Active Continental Margins

Continental margins can be classified as either passive or active, depending on their proximity to plate boundaries. **Passive margins** (Figure 3.7, *left side*) are embedded within the interior of lithospheric plates and are therefore not in close proximity to any plate boundary. Thus, passive margins usually lack major tectonic activity (such as large earthquakes, eruptive volcanoes, and mountain building).

The East Coast of the United States, where there is no plate boundary, is an example of a passive continental margin. Passive margins are usually produced by rifting of continental landmasses and continued sea floor spreading over geologic time. Features of passive continental margins include the continental shelf, the continental slope, and the continental rise that extends toward the deep-ocean basins (Figures 3.7 and 3.8).

Active margins (Figure 3.7, *right side*) are associated with lithospheric plate boundaries and are marked by a high degree of tectonic activity. Two types of active margins exist. **Convergent active margins** are associated with oceanic–continental convergent plate boundaries. From the land to the ocean, features include an onshore arc-shaped row of active volcanoes, then a narrow shelf, a steep slope, and an offshore trench that delineates the plate boundary. Western South America, where the Nazca Plate is being subducted beneath the South American Plate, is an example of a convergent active margin. **Transform active margins** are less common and are associated with transform plate boundaries. At these locations, offshore faults usually parallel the main transform plate boundary fault and create linear islands, banks (shallowly submerged areas), and deep basins close to shore. Coastal California along the San Andreas Fault is an example of a transform active margin.

KEY CONCEPT

Passive continental margins lack a plate boundary and have different features than active continental margins, which include a plate boundary (either convergent or transform).

Continental Shelf

The **continental shelf** is defined as a generally flat zone extending from the shore beneath the ocean surface to a point at which a marked increase in slope angle occurs, called the **shelf break** (Figure 3.8). It is usually flat and relatively featureless because of marine sediment deposits but can contain coastal islands, reefs, and raised banks. The underlying rock is granitic continental crust, so the continental shelf is geologically part of the continent. Accurate sea floor mapping is essential for determining the extent of the continental shelf, which has come into question recently in the Arctic Ocean. The general bathymetry of the continental shelf can usually be predicted by examining the topography of the adjacent land.

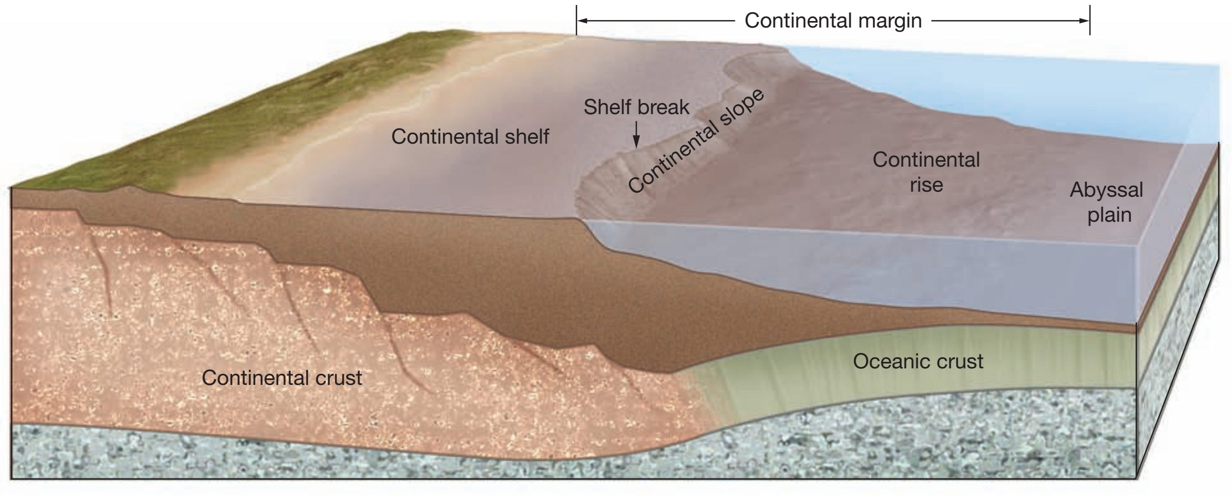


FIGURE 3.8 Features of a passive continental margin. Schematic view showing the main features of a passive continental margin.

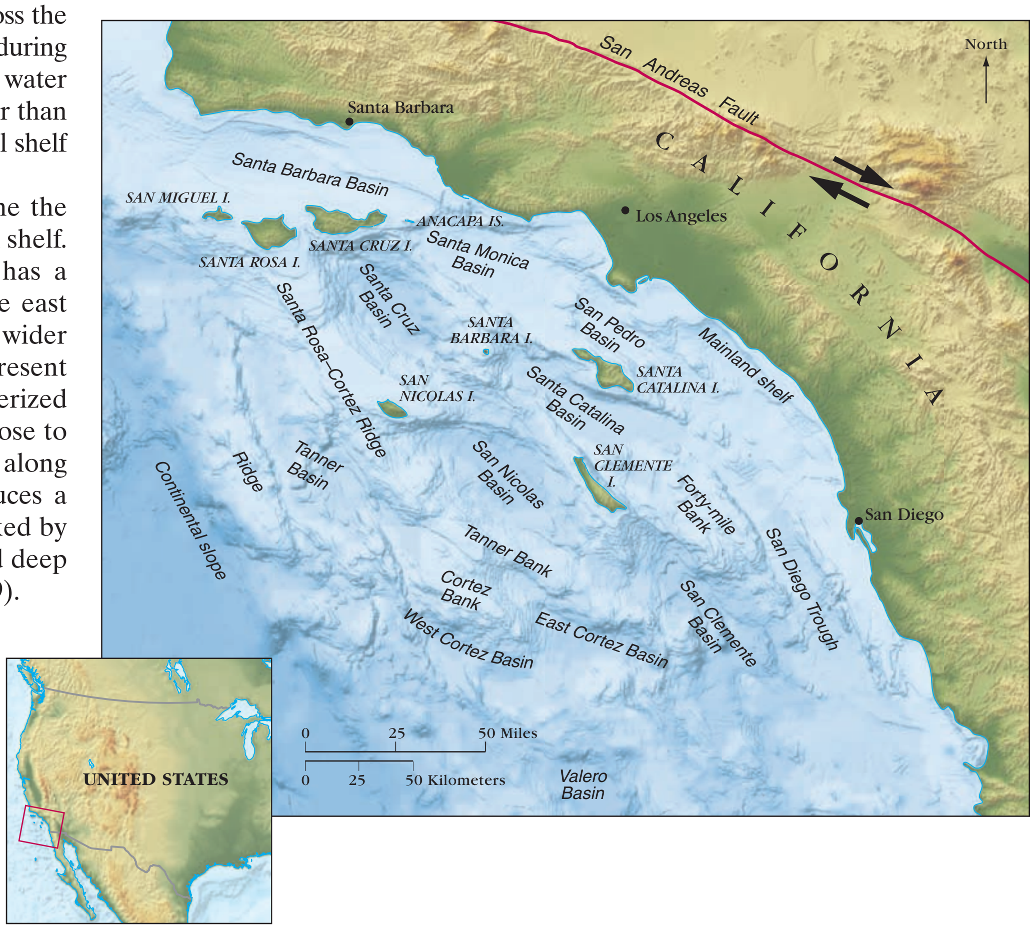
With few exceptions, the coastal topography extends beyond the shore and onto the continental shelf.

The average width of the continental shelf is about 70 kilometers (43 miles), but it varies from a few tens of meters to 1500 kilometers (930 miles). The broadest shelves occur off the northern coasts of Siberia and North America in the Arctic Ocean. The average depth at which the shelf break occurs is about 135 meters (443 feet). Around the continent of Antarctica, however, the shelf break occurs at 350 meters (2200 feet). The average slope of the continental shelf is only about a tenth of a degree, which is similar to the slope given to a large parking lot for drainage purposes.

Sea level has fluctuated over the history of Earth, causing the shoreline to migrate back and forth across the continental shelf. When colder climates prevailed during the most recent ice age, for example, more of Earth's water was frozen as glaciers on land, so sea level was lower than it is today. During that time, more of the continental shelf was exposed.

The type of continental margin will determine the shape and features associated with the continental shelf. For example, the east coast of South America has a broader continental shelf than its west coast. The east coast is a passive margin, which typically has a wider shelf. In contrast, the convergent active margin present along the west coast of South America is characterized by a narrow continental shelf and a shelf break close to shore. For transform active margins such as along California, the presence of offshore faults produces a continental shelf that is not flat. Rather, it is marked by a high degree of relief (islands, shallow banks, and deep basins) called a **continental borderland** (Figure 3.9).

FIGURE 3.9 Continental borderland. A continental borderland, like the one offshore Southern California, consists of a series of islands, shallow banks, and deep basins. It is a result of its proximity to the San Andreas Fault, a major transform plate boundary.



Continental Slope

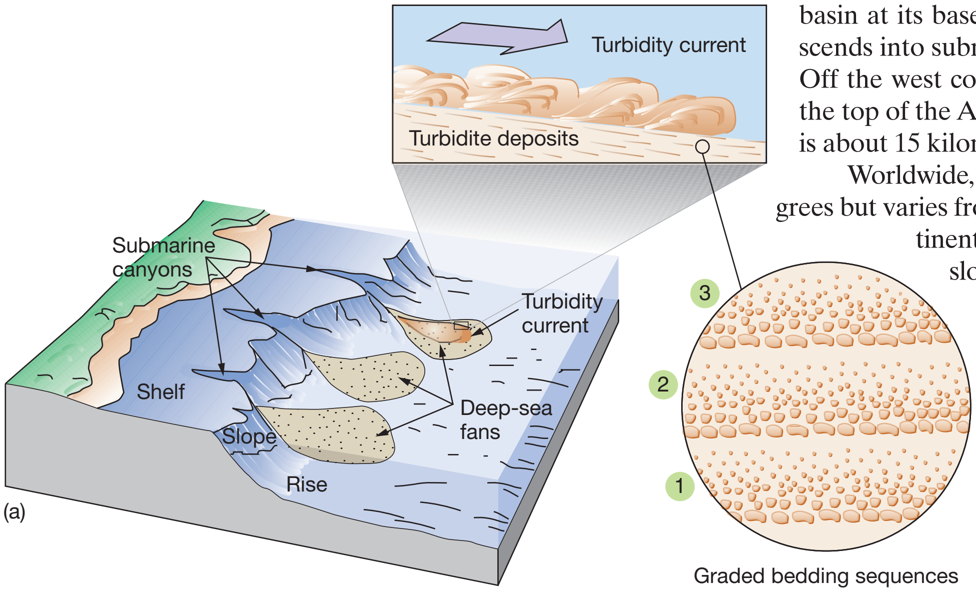
The **continental slope**, which lies beyond the shelf break, is where the deep-ocean basins begin. Total relief in this region is similar to that found in mountain ranges on the continents. The break at the top of the slope may be from 1 to 5 kilometers (0.6 to 3 miles) above the deep-ocean basin at its base. Along convergent active margins where the slope descends into submarine trenches, even greater vertical relief is measured. Off the west coast of South America, for instance, the total relief from the top of the Andes Mountains to the bottom of the Peru–Chile Trench is about 15 kilometers (9.3 miles).

Worldwide, the slope of the continental slopes averages about 4 degrees but varies from 1 to 25 degrees.[5] A study that compared different continental slopes in the United States revealed that the average slope is just over 2 degrees. Around the margin of the Pacific Ocean, the continental slopes average more than 5 degrees because of the presence of convergent active margins that drop directly into deep offshore trenches. The Atlantic and Indian Oceans, on the other hand, contain many passive margins, which lack plate boundaries. Thus, the amount of relief is lower and slopes in these oceans average about 3 degrees.

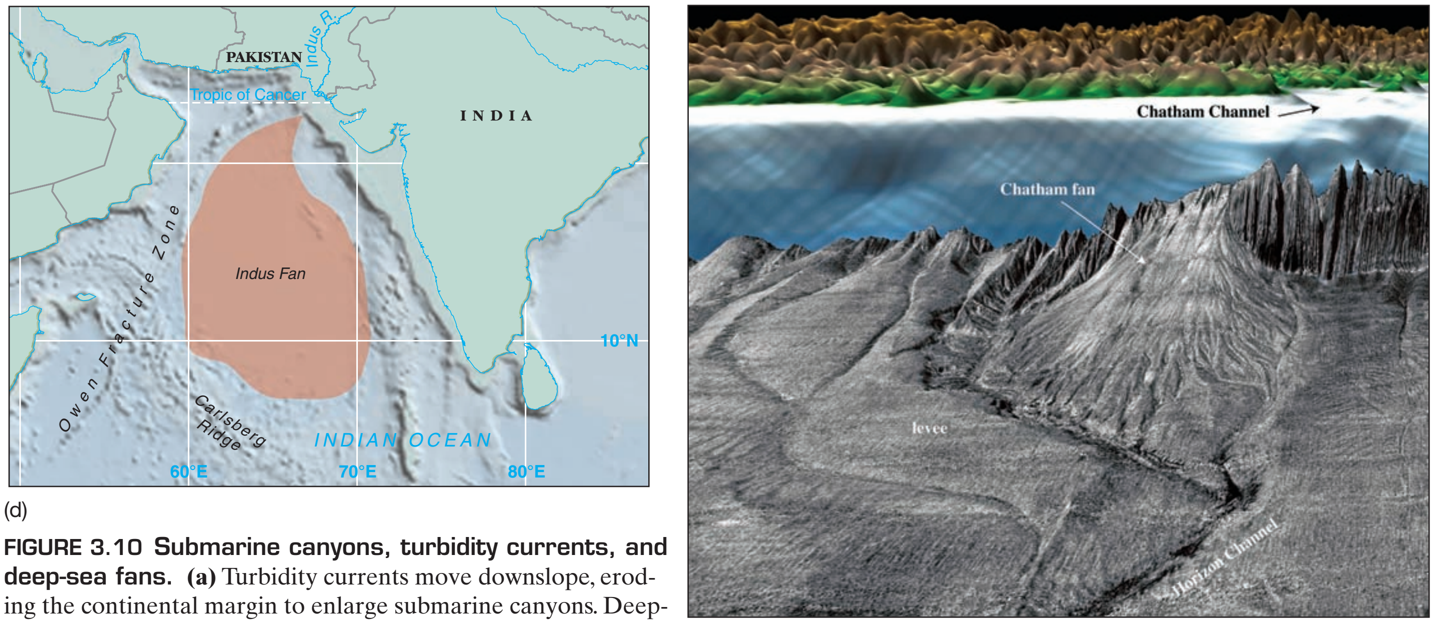
Submarine Canyons and Turbidity Currents

The continental slope—and, to a lesser extent, the continental shelf—exhibit **submarine canyons**, which are narrow but deep submarine valleys that are V-shaped in profile view and have branches or tributaries with steep to overhanging walls (Figure 3.10). They resemble canyons formed on land that are carved by rivers and can be quite large. In fact, the Monterey Canyon off California is comparable in size to Arizona's Grand Canyon (Figure 3.11).

How are submarine canyons formed? Initially it was thought submarine canyons were ancient




(b)
(c)



(d)
(e)

FIGURE 3.10 Submarine canyons, turbidity currents, and deep-sea fans. (a) Turbidity currents move downslope, eroding the continental margin to enlarge submarine canyons. Deep-sea fans are composed of turbidite deposits, which consist of sequences of graded bedding (*inset*). **(b)** A diver descends into La Jolla Submarine Canyon, offshore California. **(c)** Outcrop of layered turbidite deposits that have been tilted and uplifted onto land in California. Each light-colored layer is sandstone that marks the coarser bottom of a graded bedding sequence. **(d)** Map of the Indus Fan, a large but otherwise typical example of a passive margin fan. **(e)** Sonar perspective view of southeast Alaska's Chatham Fan, which rises 450 meters (1500 feet) above the surrounding sea floor. Vertical exaggeration is 20 times; view looking northeast.

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[5] For comparison, the windshield of an aerodynamically designed car has a slope of about 25 degrees.

river valleys created by the erosive power of rivers when sea level was lower and the continental shelf was exposed. Although some canyons are directly offshore from where rivers enter the sea, the majority of them are not. Many, in fact, are confined exclusively to the continental slope. In addition, submarine canyons continue to the base of the continental slope, which averages some 3500 meters (11,500 feet) below sea level. There is no evidence, however, that sea level has ever been lowered by that much.

Side-scan sonar surveys along the Atlantic coast indicate that the continental slope is dominated by submarine canyons from Hudson Canyon near New York City to Baltimore Canyon in Maryland. Canyons confined to the continental slope are straighter and have steeper canyon floor gradients than those that extend into the continental shelf. These characteristics suggest the canyons are created on the continental slope by some marine process and enlarge into the continental shelf through time.

Both indirect and direct observation of the erosive power of **turbidity** (*turbidus* = disordered) **currents** (Box 3.2) has suggested that they are responsible for carving submarine canyons. Turbidity currents are underwater avalanches of muddy water mixed with rocks and other debris. The sediment portion of turbidity currents comes from sea floor materials that move across the continental shelf into the head of a submarine canyon and accumulate there, setting the stage for initiation of a turbidity current. Trigger mechanisms for turbidity currents include shaking by an earthquake, the oversteepening of sediment that accumulates on the shelf, hurricanes passing over the area, and the rapid input of sediment from flood waters. Once a turbidity current is set in motion, the dense mixture of water and debris moves rapidly downslope under the force of gravity and carves the canyon as it goes, resembling a flash flood on land. Turbidity currents are strong enough to transport huge rocks down submarine canyons and do a considerable amount of erosion over time.

Continental Rise

The **continental rise** is a transition zone between the continental margin and the deep-ocean floor comprised of a huge submerged pile of debris. Where did all this debris come from, and how did it get there?

The existence of turbidity currents suggests that the material transported by these currents is responsible for the creation of continental rises. When a turbidity current moves through and erodes a submarine canyon, it exits through the mouth of the canyon. The slope angle decreases and the turbidity current slows, causing suspended material to settle out in a distinctive type of layering called **graded bedding** that *grades in size upward* (Figure 3.10a, *inset*). As the energy of the turbidity current dissipates, larger pieces settle first, then progressively smaller pieces settle, and eventually even very fine pieces settle out, which may occur weeks or months later.

An individual turbidity current deposits one graded bedding sequence. The next turbidity current may partially erode the previous deposit and then deposit another graded bedding sequence on top of the previous one. After some time, a thick sequence of graded bedding deposits can develop one on top of another. These stacks of graded bedding are called **turbidite deposits** (Figure 3.10c), of which the continental rise is composed.

As viewed from above, the deposits at the mouths of submarine canyons are fan, lobate, or apron shaped (Figure 3.10a and 3.10e). Consequently, these deposits are called **deep-sea fans**, or **submarine fans**. Deep-sea fans create the continental rise when they merge together along the base of the continental slope. Along convergent active margins, however, the steep continental slope leads directly into a deep-ocean trench. Sediment from turbidity currents accumulates in the trench and there is no continental rise.

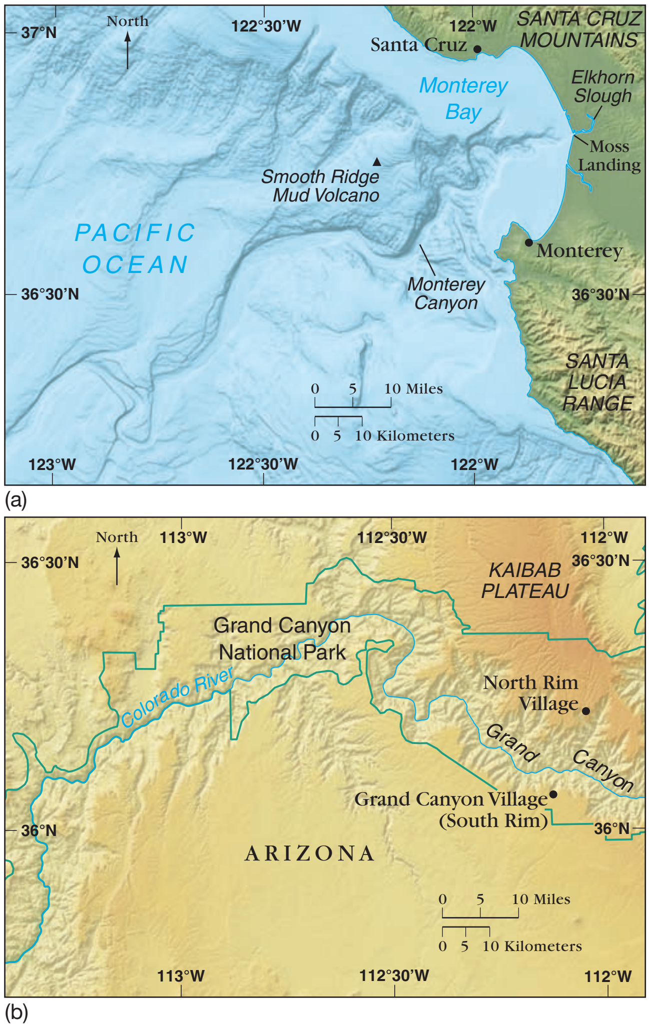


FIGURE 3.11 Comparison of the Monterey Submarine Canyon and Arizona's Grand Canyon. In these same-scale maps, it can be seen that the Monterey Submarine Canyon **(a)** is comparable to Arizona's Grand Canyon **(b)** in terms of length, depth, width, and steepness.

KEY CONCEPT

Turbidity currents are underwater avalanches of muddy water mixed with sediment that move down the continental slope and are responsible for carving submarine canyons.

web animation

Turbidity Currents and Graded Bedding

WEB VIDEO

Turbidity Current Flume Experiment

3.2 RESEARCH METHODS IN OCEANOGRAPHY

A GRAND "BREAK": EVIDENCE FOR TURBIDITY CURRENTS

How do earthquakes and telephone cables help explain how turbidity currents move across the ocean floor and carve submarine canyons? In 1929, the $M_w = 7.2$ Grand Banks earthquake in the North Atlantic Ocean severed some of the trans-Atlantic telegraph cables that lay across the sea floor south of Newfoundland near the earthquake epicenter (Figure 3D). At first, it was assumed that sea floor movement caused all these breaks. However, analysis of the data revealed that the cables closest to the earthquake broke simultaneously with the earthquake, but cables that crossed the slope and deeper ocean floor at greater distances from the earthquake were broken progressively later in time. It seemed unusual that certain cables were affected by the failure of the slope due to ground shaking but others were broken several minutes later.

The mystery was solved several years later, when reanalysis of the event suggested that the earthquake triggered a major submarine landslide and initiated a turbidity current, which moved down the slope and was responsible for the successive cable breaks. How fast do turbidity currents move? By studying the pattern of broken cables, scientists determined that the turbidity current in this case reached speeds of about 80 kilometers (50 miles) per hour on the steep portions of the continental slope and about 24 kilometers (15 miles) per hour on the more gently sloping continental rise. The study showed that turbidity currents can reach high speeds and are strong enough to break underwater cables, suggesting that they must be powerful enough to erode submarine canyons.

Further evidence of turbidity currents comes from several sonar studies that have documented turbidity currents. For instance, a study of Rupert Inlet in British Columbia, Canada, monitored turbidity currents moving through an underwater channel. These studies indicate that submarine canyons are carved by turbidity currents over long periods of time, just as canyons on land are carved by running water.

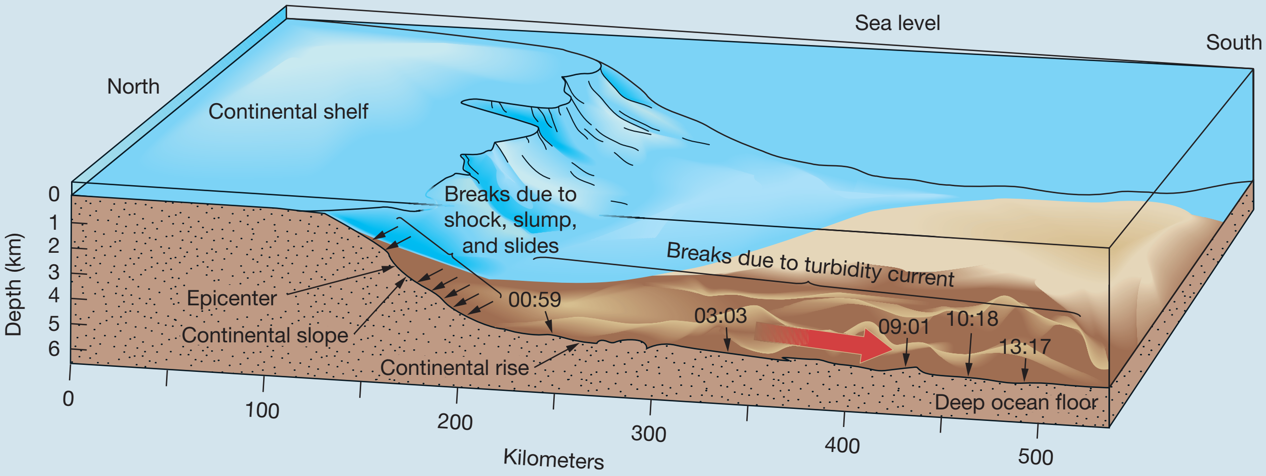


FIGURE 3D Grand Banks earthquake. Diagrammatic view of the sea floor showing the sequence of events for the 1929 Grand Banks earthquake. The epicenter is the point on Earth's surface directly above the earthquake. The arrows point to cable breaks; the numbers show times of breaks in hours and minutes after the earthquake. Vertical scale is greatly exaggerated.

One of the largest deep-sea fans in the world is the Indus Fan, a passive margin fan that extends 1800 kilometers (1100 miles) south of Pakistan (Figure 3.10d). The Indus River carries extensive amounts of sediment from the Himalaya Mountains to the coast. This sediment eventually makes its way down the submarine canyon and builds the fan, which, in some areas, has sediment that is more than 10 kilometers (6.2 miles) thick. The Indus Fan has a main submarine canyon channel extending seaward onto the fan but soon divides into several branching distributary channels. These distributary channels are similar to those found on deltas, which form at the mouths of streams. On the lower fan, the surface has a very low slope, and the flow is no longer confined to channels, so it spreads out and forms layers of fine sediment across the fan surface. The Indus Fan has so much sediment, in fact, that it partially buries an active mid-ocean ridge, the Carlsberg Ridge!

3.4 What Features Exist in the Deep-Ocean Basins?

The deep-ocean floor lies beyond the continental margin province (the shelf, slope, and the rise) and contains a variety of features.

Abyssal Plains

Extending from the base of the continental rise into the deep-ocean basins are flat depositional surfaces with slopes of less than a fraction of a degree that cover extensive portions of the deep-ocean basins. These **abyssal** (*a* = without, *byssus* = bottom) **plains** average between 4500 meters (15,000 feet) and 6000 meters (20,000 feet) deep. They are not literally bottomless, but they are some of the deepest (and flattest) regions on Earth.

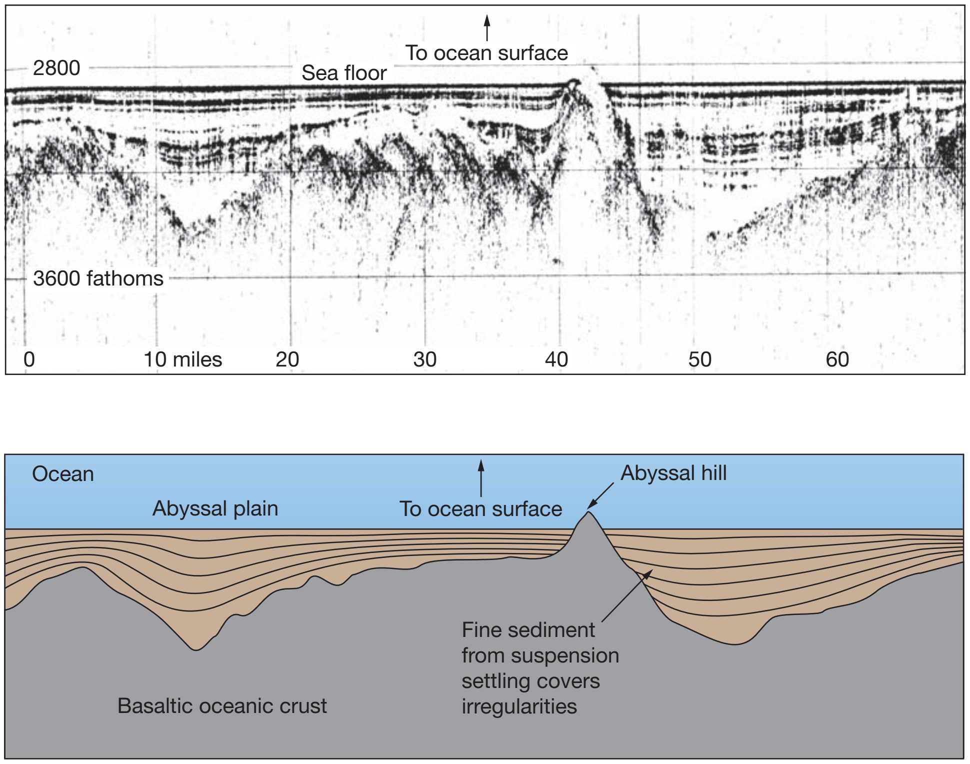


FIGURE 3.12 Abyssal plain formed by suspension settling. Seismic cross section (*above*) and matching drawing (*below*) for a portion of the deep Madeira Abyssal Plain in the eastern Atlantic Ocean, showing the irregular volcanic terrain buried by sediments.

Abyssal plains are formed by fine particles of sediment slowly drifting onto the deep-ocean floor. Over millions of years, a thick blanket of sediment is produced by **suspension settling** as fine particles (analogous to "marine dust") accumulate on the ocean floor. With enough time, these deposits cover most irregularities of the deep ocean, as shown in Figure 3.12. In addition, sediment traveling in turbidity currents from land adds to the sediment load.

The type of continental margin determines the distribution of abyssal plains. For instance, few abyssal plains are located in the Pacific Ocean; instead, most occur in the Atlantic and Indian Oceans. The deep-ocean trenches found on the convergent active margins of the Pacific Ocean prevent sediment from moving past the continental slope. In essence, the trenches act like a gutter that traps sediment transported off the land by turbidity currents. On the passive margins of the Atlantic and Indian Oceans, however, turbidity currents travel directly down the continental margin and deposit sediment on the abyssal plains. In addition, the distance from the continental margin to the floor of the deep-ocean basins in the Pacific Ocean is so great that most of the suspended sediment settles out before it reaches these distant regions. Conversely, the smaller size of the Atlantic and Indian Oceans does not prevent suspended sediment from reaching their deep-ocean basins.

Volcanic Peaks of the Abyssal Plains

Poking through the sediment cover of the abyssal plains are a variety of volcanic peaks, which extend to various elevations above the ocean floor. Some extend above sea level to form islands while others are just below the surface (see Web Box 3.2). Those that are below sea level but rise more than 1 kilometer (0.6 mile) above the deep-ocean floor and have a pointy top like an upside-down ice cream cone are called **seamounts**. Worldwide, there are more than 50,000 known seamounts, and scientists estimate that seamounts could number as high as 200,000. On the other hand, if a volcano has a flattened top, it is called a

tablemount, or *guyot*. The origin of seamounts and tablemounts was discussed as a piece of supporting evidence for plate tectonics in Chapter 2 (refer to Figure 2.26).

Volcanic features on the ocean floor that are less than 1000 meters (0.6 mile) tall—the minimum height of a seamount—are called **abyssal hills**, or **seaknolls**. Abyssal hills are one of the most abundant features on the planet (several hundred thousand have been identified) and cover a large percentage of the entire ocean basin floor. Many are gently rounded in shape, and they have an average height of about 200 meters (650 feet). Most abyssal hills are created by stretching of crust during the creation of new sea floor at the mid-ocean ridge.

In the Atlantic and Pacific Oceans, many abyssal hills are found buried beneath abyssal plain sediment. In the Pacific Ocean, the abundance of active margins traps land-derived sediment and so the rate of sediment deposition is lower. Consequently, extensive regions dominated by abyssal hills have resulted; these are called **abyssal hill provinces**. The evidence of volcanic activity on the bottom of the Pacific Ocean is particularly widespread. In fact, more than 20,000 volcanic peaks are known to exist on the Pacific sea floor.

Ocean Trenches and Volcanic Arcs

Along passive margins, the continental rise commonly occurs at the base of the continental slope and merges smoothly into the abyssal plain. In convergent active margins, however, the slope descends into a long, narrow, steep-sided **ocean trench**. Ocean trenches are deep linear scars in the ocean floor, caused by the collision of two plates along convergent plate margins (as discussed in Chapter 2). The landward side of the trench rises as a **volcanic arc** that may produce islands (such as the islands of Japan, an **island arc**) or a volcanic mountain range along the margin of a continent (such as the Andes Mountains, a **continental arc**).

The deepest portions of the world's oceans are found in these trenches. In fact, the deepest point on Earth's surface—11,022 meters (36,161 feet)—is found in the Challenger Deep area of the Mariana Trench. The majority of ocean trenches are found along the margins of the Pacific Ocean (Figure 3.13), while only a few exist in the Atlantic and Indian Oceans.

THE PACIFIC RING OF FIRE The **Pacific Ring of Fire** occurs along the margins of the Pacific Ocean. It has the majority of Earth's active volcanoes and large earthquakes because of the prevalence of convergent plate boundaries along the Pacific Rim. A part of the Pacific Ring of Fire is South America's western coast, including the Andes Mountains and the associated Peru–Chile Trench. Figure 3.14 shows a cross-sectional view of this area and illustrates the tremendous amount of relief at convergent plate boundaries where deep-ocean trenches are associated with tall volcanic arcs.

KEY CONCEPT

Deep-ocean trenches and volcanic arcs are a result of the collision of two plates at convergent plate boundaries and mostly occur along the margins of the Pacific Ocean (Pacific Ring of Fire).

3.5 What Features Exist Along the Mid-Ocean Ridge?

The global mid-ocean ridge is a continuous, fractured-looking mountain ridge that extends through all the ocean basins. The portion of the mid-ocean ridge found in the North Atlantic Ocean is called the Mid-Atlantic Ridge (Figure 3.15), which dwarfs all mountain ranges on land. As discussed in Chapter 2, the mid-ocean ridge results from sea floor spreading along divergent plate boundaries. The enormous mid-ocean ridge forms Earth's longest mountain chain, extending across some 75,000 kilometers (46,600 miles) of the deep-ocean basin. The width of the mid-ocean ridge averages about 1000 kilometers (620 miles). The mid-ocean ridge is a topographically high feature, extending an average of 2.5 kilometers (1.5 miles)

Selected Pacific Ocean Trenches

Name	Depth (km)	Width (km)	Length (km)
Middle America	6.7	40	2800
Aleutian	7.7	50	3700
Peru-Chile	8.0	100	5900
Kermadec-Tonga	10.0	50	2900
Kuril	10.5	120	2200
Mariana	11.0	70	2550

Atlantic Ocean Trenches

Name	Depth (km)	Width (km)	Length (km)
South Sandwich	8.4	90	1450
Puerto Rico	8.4	120	1550

Indian Ocean Trenches

Name	Depth (km)	Width (km)	Length (km)
Java (Sunda)	7.5	80	4500

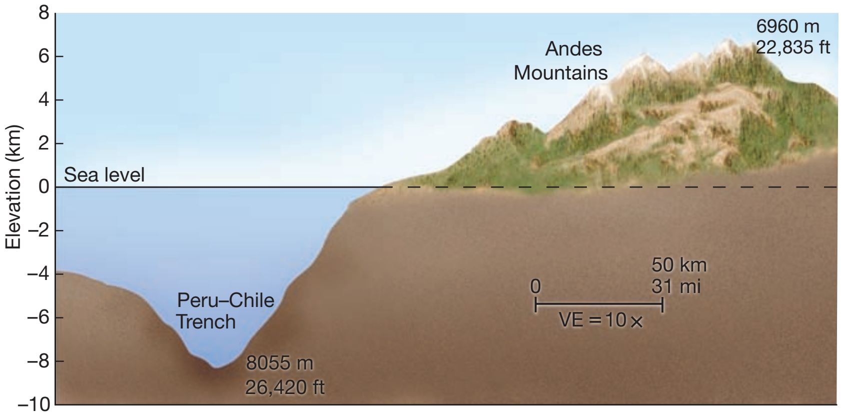
FIGURE 3.13 Location and dimensions of ocean trenches. The majority of ocean trenches are along the margins of the Pacific Ocean where plates are being subducted. Most of the world's large earthquakes (due to subduction) and active volcanoes (as volcanic arcs) occur around the Pacific Rim, which is why the area is also called the Pacific Ring of Fire.

above the surrounding sea floor. The mid-ocean ridge contains only a few scattered islands, such as Iceland and the Azores, where it peeks above sea level. Remarkably, the mid-ocean ridge covers 23% of Earth's surface.

The mid-ocean ridge is entirely volcanic and is composed of basaltic lavas characteristic of the oceanic crust. Along most of its crest is a central downdropped **rift valley** created by sea floor spreading (rifting) where two plates diverge (see, for example, Figure 2.15 and Figure 2.16). Along the Mid-Atlantic Ridge, for example, is a central rift valley that is as much as 30 kilometers (20 miles) wide and 3 kilometers (2 miles) deep. Here, molten rock presses upward toward the sea floor, setting off earthquakes, creating jets of superheated seawater, and eventually solidifying to form new oceanic crust. Cracks called *fissures* (*fissus* = split) and faults are commonly observed in the central rift valley. Swarms of small earthquakes occur along the central rift valley caused by the injection of magma into the sea floor or rifting along faults.

Segments of the mid-ocean ridge called **oceanic ridges** have a prominent rift valley and steep, rugged slopes, and **oceanic rises** have slopes that are gentler and less rugged. As explained

FIGURE 3.14 Profile across the Peru–Chile Trench and the Andes Mountains. Over a distance of 200 kilometers (125 miles), there is a change in elevation of more than 14,900 meters (49,000 feet) from the Peru–Chile Trench to the Andes Mountains. This dramatic relief is a result of plate interactions at a convergent active margin, producing a deep-ocean trench and associated continental volcanic arc. Vertical scale is exaggerated 10 times.



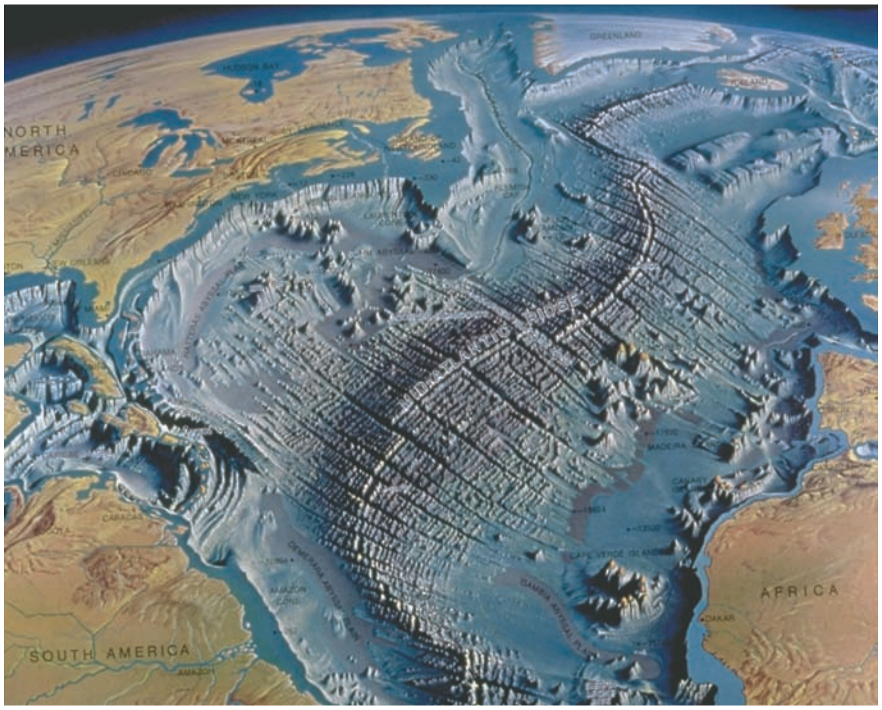


FIGURE 3.15 Floor of the North Atlantic Ocean. The global mid-ocean ridge cuts through the center of the Atlantic Ocean, where it is called the Mid-Atlantic Ridge.

in Chapter 2, the differences in overall shape are caused by the fact that oceanic ridges (such as the Mid-Atlantic Ridge) spread more slowly than oceanic rises (such as the East Pacific Rise).

Volcanic Features

Volcanic features associated with the mid-ocean ridge include tall volcanoes called *seamounts*[6] (Figure 3.16a) and recent underwater lava flows. When hot basaltic lava spills onto the sea floor, it is exposed to cold seawater that chills the margins of the lava. This creates **pillow lavas** or **pillow basalts**, which are smooth, rounded lobes of rock that resemble a stack of bed pillows (Figure 3.16b and 3.16c).

Although most people are usually not aware of it, frequent volcanic activity is common along the mid-ocean ridge. In fact, 80% of Earth's volcanic activity takes place on the sea floor, and every year about 12 cubic kilometers (3 cubic miles) of molten rock erupts underwater. The amount of erupted lava along the mid-ocean ridge is large enough to fill an Olympic-sized swimming pool every three seconds! Bathymetric studies along the Juan de Fuca Ridge off Washington and Oregon, for example, revealed that 50 million cubic meters (1800 million cubic feet) of new lava were released sometime between 1981 and 1987. Subsequent surveys of the area indicated many changes along the mid-ocean ridge, including new volcanic features, recent lava flows, and depth changes of up to 37 meters (121 feet). Interest in the continuing volcanic activity along the Juan de Fuca Ridge has led to the development of a permanent sea floor observation system there (see Box 2.2). Other parts of the mid-ocean ridge, such as East Pacific Rise, also experience frequent volcanic activity (Box 3.3).

Hydrothermal Vents

Other features in the central rift valley include **hydrothermal** (*hydro* = water, *thermo* = heat) **vents**. Hydrothermal vents are sea floor hot springs created when cold seawater seeps down along cracks and fractures in the ocean crust and approaches an underground magma chamber (Figure 3.17). The water picks up heat

WEB VIDEO

Formation of Pillow Lava

STUDENTS SOMETIMES ASK...

What effect does all this volcanic activity along the mid-ocean ridge have at the ocean's surface?

Sometimes an underwater volcanic eruption is large enough to create what is called a *megaplume* of warm, mineral-rich water that is lower in density than the surrounding seawater and thus rises to the surface. Remarkably, a few research vessels have reported experiencing the effects of a megaplume at the surface while directly above an erupting sea floor volcano! Researchers on board describe bubbles of gas and steam at the surface, a marked increase in water temperature, and the presence of enough volcanic material to turn the water cloudy. In terms of warming the ocean, the heat released into the ocean at mid-ocean ridges is probably not very significant, mostly because the ocean is so good at absorbing and redistributing heat.

STUDENTS SOMETIMES ASK...

Has anyone seen pillow lava forming?

Amazingly, yes! In the 1960s, an underwater film crew ventured to Hawaii during an eruption of the volcano Kilauea, where lava spilled into the sea. They braved high water temperatures and risked being burned on the red-hot lava but filmed some incredible footage. Underwater, the formation of pillow lava occurs where a tube emits molten lava directly into the ocean. When hot lava comes into contact with cold seawater, it forms the characteristic smooth and rounded margins of pillow basalt. The divers also experimented with a hammer on newly formed pillows and were able to initiate new lava outpourings.

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[6] In a number of cases, researchers have discovered seamounts that initially formed along the crest of the mid-ocean ridge and have been split in two as the plates spread apart.

and dissolved substances and then works its way back toward the surface through a complex plumbing system, exiting through the sea floor. The temperature of the water that rushes out of a particular hydrothermal vent determines its appearance:

- **Warm-water vents** have water temperatures below 30°C (86°F) and generally emit water that is clear in color.
- **White smokers** have water temperatures from 30° to 350°C (86° to 662°F) and emit water that is white because of the presence of various light-colored compounds, including barium sulfide.
- **Black smokers** have water temperatures above 350°C (662°F) and emit water that is black because of the presence of dark-colored **metal sulfides**, including iron, nickel, copper, and zinc.

STUDENTS SOMETIMES ASK . . .

If black smokers are so hot, why isn't there steam coming out of them instead of hot water?

Indeed, black smokers emit water that can be up to four times the boiling point of water at the ocean's surface and hot enough to melt lead. However, the depth where black smokers are found results in much higher pressure than at the surface. At these higher pressures, water has a much higher boiling point. Thus, water from hydrothermal vents remains in the liquid state instead of turning into water vapor (steam).

Many black smokers spew out of chimney-like structures (Figure 3.17b) that can be up to 60 meters (200 feet) high and were named for their resemblance to factory smokestacks belching clouds of smoke. The dissolved metal particles often come out of solution, or **precipitate**,[7] when the hot water mixes with cold seawater, creating coatings of mineral deposits on nearby rocks. Chemical analyses of these deposits reveal that they are composed of various metal sulfides and sometimes even silver and gold.

In addition, most hydrothermal vents foster unusual deep-ocean ecosystems that include organisms such as giant tubeworms, large clams, beds of mussels, and many other creatures—most of which were new to science when they were first encountered. These organisms are able to survive in the absence of sunlight because the vents discharge hydrogen sulfide gas, which is metabolized by archaeons[8] and bacteria and provides a food source for other organisms in the community. Recent studies of active hydrothermal vent fields indicate that vents have short life spans of only a few years to several decades, which has important implications for the organisms that depend on hydrothermal vents. The interesting associations of these organisms are discussed in Chapter 15, "Animals of the Benthic Environment."

Fracture Zones and Transform Faults

The mid-ocean ridge is cut by a number of **transform faults**, which offset spreading zones. Oriented perpendicular to the spreading zones, transform faults give the mid-ocean ridge the zigzag appearance seen in Figure 3.15. As described in Chapter 2, transform faults occur to accommodate spreading of a linear ridge system on a spherical Earth and because different segments of the mid-ocean ridge spread apart at different rates.

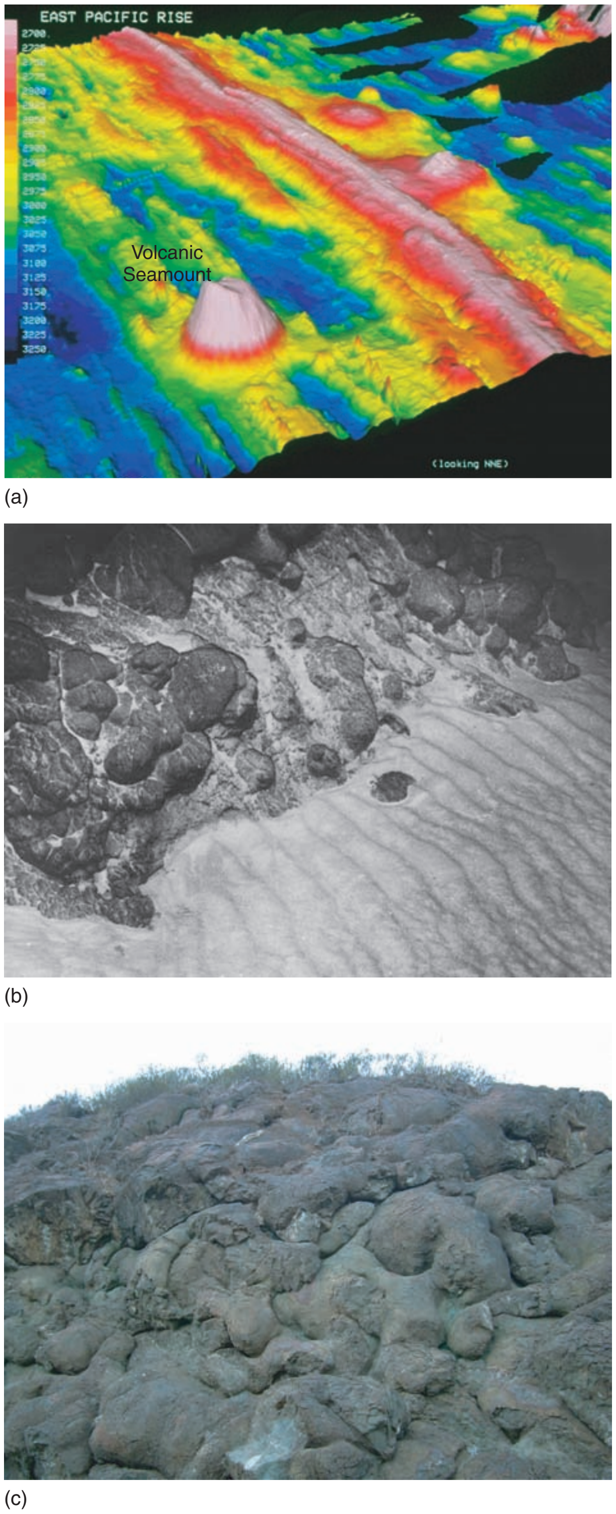

FIGURE 3.16 Mid-ocean ridge volcanoes and pillow lava. **(a)** False-color perspective view based on sonar mapping of a portion of the East Pacific Rise (*center*) showing volcanic seamount (*left*). The depth, in meters, is indicated by the color scale along the left margin; vertical exaggeration is six times. **(b)** Recently formed pillow lava along the East Pacific Rise. Photo shows an area of the sea floor about 3 meters (10 feet) across that also displays ripple marks from deep-ocean currents. **(c)** Pillow lava that was once on the sea floor but has since been uplifted onto land at Port San Luis, California. Maximum width of an individual pillow is 1 meter (3 feet).

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[7] A *chemical precipitate* is formed whenever dissolved materials change from existing in the dissolved state to existing in the solid state.

[8] Archaeons are microscopic bacteria-like organisms—a newly discovered domain of life.

3.3 RESEARCH METHODS IN OCEANOGRAPHY

RECOVERING OCEANOGRAPHIC EQUIPMENT STUCK IN LAVA

Although the mid-ocean ridge is one of the most active features on the planet and experiences an abundance of volcanic activity, nobody has ever directly observed an undersea volcanic eruption there. However, a team of oceanographers on a research cruise to the East Pacific Rise in 2006 came close to this remarkable feat.

The story starts a year earlier, when scientists deployed 12 ocean-bottom seismometers (OBSs) over a few square kilometers of sea floor along an unusually active portion of the East Pacific Rise that is about 725 kilometers (450 miles) south of Acapulco, Mexico, and 2.5 kilometers (1.6 miles) deep. The OBSs—each about the size and weight of a small refrigerator—are designed to stay on the sea floor for up to a year and collect seismic data. Researchers returned in 2006, thinking that they would simply recover the instruments and send down others. When the research vessel sent a sonar signal to the OBSs to release their weights and use their floats to return to the surface, only four came bobbing up. That's when the scientists suspected that a volcanic eruption had occurred. Three other OBSs responded to the signal but did not come to the surface, and five other instruments were not heard from, presumably because they were buried in lava.

Two months later, scientists returned with a camera-equipped sled that is towed behind a ship and were able to locate the three OBSs embedded in recent lava. Although they tried to nudge and pry them loose with the sled, the OBSs were thoroughly stuck. Wanting to retrieve the stuck OBSs with the hope that they had recorded data while riding out an active sea floor lava flow, the scientists had to wait until a year later, when the tethered robotic vehicle *Jason* was sent down to try to free the instruments. Using *Jason*'s video camera and its mechanical arms controlled remotely from a command center on the ship, the crew was able to pry away large chunks of lava that locked the instruments in place. After much yanking, two of the OBSs finally broke free and rose to the surface, with help from attached floats. Although the researchers attempted to free the third OBS, it was never recovered because it was stuck too tightly in lava.

The recovered OBS instruments—although badly scorched from the hot lava (Figure 3E)—had usable data that have given researchers new information about the volcanic processes that occur at the mid-ocean ridge. This and other evidence suggests that the fresh lava had erupted for six hours straight, heating and darkening the water above it and spreading along the ridge for more than 16 kilometers (10 miles). The researchers consider themselves lucky to have fortuitously caught Earth's crust in the very act of ripping itself apart, documenting swarms of undersea earthquakes and culminating in a volcanic eruption that buried their instruments in lava.

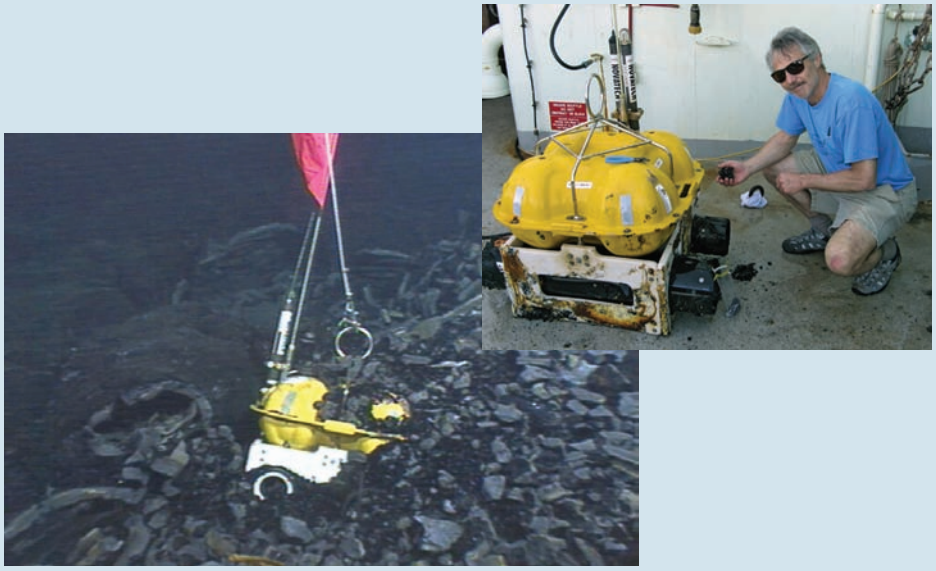


FIGURE 3E An ocean-bottom seismometer (OBS) stuck in lava. A 2006 sea floor eruption along the East Pacific Rise trapped this and several other OBS instruments in lava. The yellow plastic covering protects glass ball floats that are normally used to raise the instrument to the surface; additional attached floats are shown above the OBS. Scientists freed the device by using a robotic vehicle to remove chunks of lava that were embedded into the instrument and singed its outer casing. Inset (*right*) shows marine geologist Dan Fornari prying off chunks of recently erupted sea floor lava from the recovered instrument.

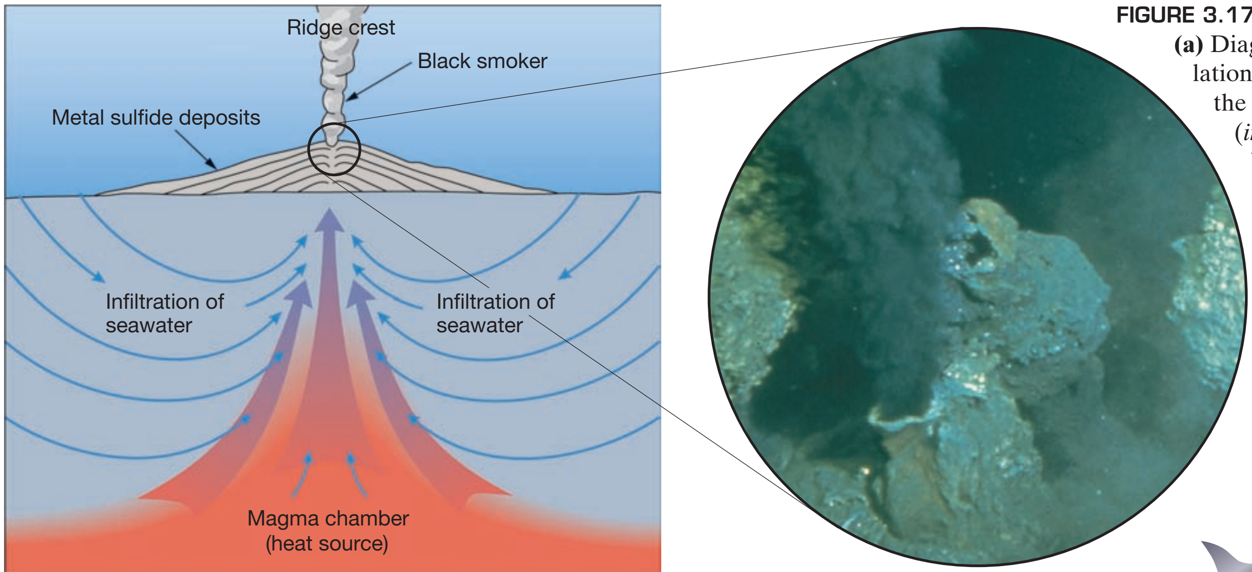
WEB VIDEO
Recovering Oceanographic
Equipment Stuck in Lava

KEY CONCEPT

The mid-ocean ridge is created by plate divergence and typically includes a central rift valley, faults and fissures, seamounts, pillow basalts, hydrothermal vents, and metal sulfide deposits.

On the Pacific Ocean sea floor, where scars are less rapidly covered by sediment than in other ocean basins, transform faults are prominently displayed (Figure 3.18). Here, they extend for thousands of kilometers away from the mid-ocean ridge and have widths of up to 200 kilometers (120 miles). These extensions, however, are not transform faults. Instead, they are **fracture zones**.

What is the difference between a transform fault and a fracture zone? Figure 3.19 shows that both run along the same long linear zone of weakness in



(a)

(b)

FIGURE 3.17 Hydrothermal vents. **(a)** Diagram showing hydrothermal circulation along the mid-ocean ridge and the creation of black smokers. Photo (*inset*) shows a close-up view of a black smoker along the East Pacific Rise. **(b)** Black smoker chimney and fissure at Susu north active site, Manus Basin, western Pacific Ocean. Chimney is about 3 meters (10 feet) tall.

Earth's crust. In fact, by following the same zone of weakness from one end to the other, it changes from a fracture zone to a transform fault and back again to a fracture zone. A transform fault is a seismically active area that offsets the axis of a mid-ocean ridge. A fracture zone, on the other hand, is a seismically inactive area that shows evidence of past transform fault activity. A helpful way to visualize the difference is that transform faults occur *between* offset segments of the mid-ocean ridge, while fracture zones occur *beyond* the offset segments of the mid-ocean ridge.

The relative direction of plate motion across transform faults and fracture zones further differentiates these two features. Across a transform fault, two lithospheric plates are moving in opposite directions. Across a fracture zone (which occurs entirely within a plate), there is no relative motion because the parts of the lithospheric plate cut by a fracture zone are moving in the same direction (Figure 3.19). Transform faults are actual plate boundaries, whereas fracture zones are not. Rather, fracture zones are ancient, inactive fault scars embedded within a plate.

In addition, earthquake activity is different in transform faults and fracture zones. Earthquakes shallower than 10 kilometers (6 miles) are common when plates move in opposite directions along transform faults. Along fracture zones, where plate motion is in the same direction, seismic activity is almost completely absent.

WEB VIDEO
Black Smoker Venting Fluid

KEY CONCEPT

Transform faults are plate boundaries that occur *between* offset segments of the mid-ocean ridge, while fracture zones are intraplate features that occur *beyond* the offset segments of the mid-ocean ridge.

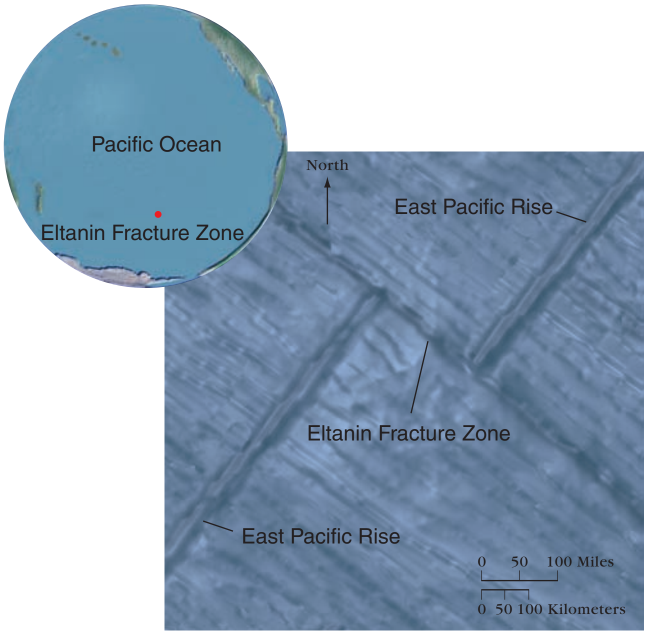


FIGURE 3.18 The Eltanin Fracture Zone. Enlargement of the Eltanin Fracture Zone in the South Pacific Ocean, showing its relationship to the East Pacific Rise. The Eltanin Fracture Zone is actually both a fracture zone and a transform fault; the name was given to it before the modern understanding of plate tectonic processes.

web animation
Transform Faults

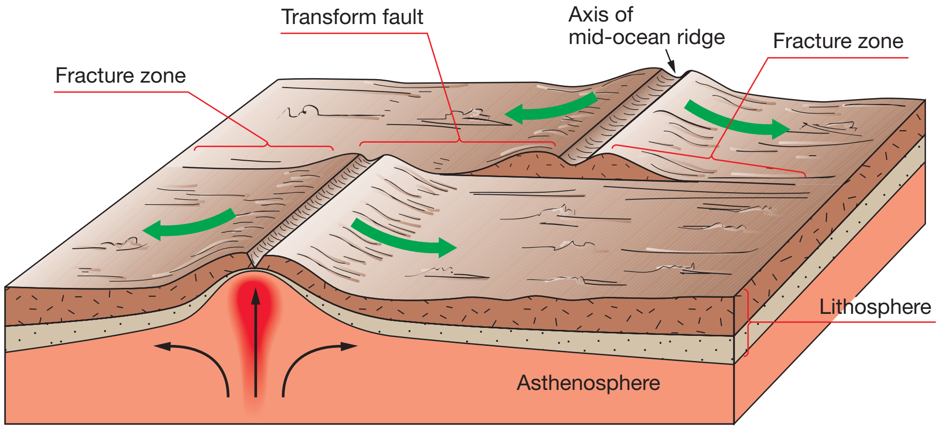


FIGURE 3.19 Transform faults and fracture zones. Transform faults are active transform plate boundaries that occur *between* the segments of the mid-ocean ridge. Fracture zones are inactive intraplate features that occur *beyond* the segments of the mid-ocean ridge.

Table 3.1 summarizes the differences between transform faults and fracture zones.

Oceanic Islands

Some of the most interesting features of ocean basins are islands, which are unusually tall features that reach from the sea floor all the way above sea level. There are three basic types of oceanic islands: (1) islands associated with volcanic activity along the mid-ocean ridge (such as Ascension Island along the Mid-Atlantic Ridge); (2) islands associated with hotspots (such as the Hawaiian Islands in the Pacific Ocean); and (3) islands that are island arcs and associated with convergent plate boundaries (such as the Aleutian Islands in the Pacific Ocean). Note that all three types are volcanic in origin. In addition, there is a fourth type of island: islands that are parts of continents (such as the British Isles off Europe), but these occur close to shore and thus do not occur in the deep ocean.

TABLE 3.1 COMPARISON BETWEEN TRANSFORM FAULTS AND FRACTURE ZONES

	Transform faults	Fracture zones
Plate boundary?	Yes—a transform plate boundary	No—an intraplate feature
Relative movement across feature	Movement in opposite directions ← ——— →	Movement in the same direction ← ——— ←
Earthquakes?	Many	Few
Relationship to mid-ocean ridge	Occur *between* offset mid-ocean ridge segments	Occur *beyond* offset mid-ocean ridge segments
Geographic examples	San Andreas Fault, Alpine Fault, Dead Sea Fault	Mendocino Fracture Zone, Molokai Fracture Zone

Chapter in Review

- *Bathymetry is the measurement of ocean depths and the charting of ocean floor topography*. The varied bathymetry of the ocean floor was first determined using *soundings* to measure water depth. Later, the development of the *echo sounder* gave ocean scientists a more detailed representation of the sea floor. Today, much of our knowledge of the ocean floor has been obtained using various *multibeam echo sounders* or *side-scan sonar instruments* (to make detailed bathymetric maps of a small area of the ocean floor); *satellite measurement* of the ocean surface (to produce maps of the world ocean floor); and *seismic reflection profiles* (to examine Earth structure beneath the sea floor).

- *Earth's hypsographic curve* shows the amount of Earth's surface area at different elevations and depths. *The distribution of area is uneven* with respect to height above or below sea level. The shape of the curve also *reflects the existence of plate tectonic processes*.

- *Continental margins can be either passive* (not associated with any plate boundaries) *or active* (associated with convergent or transform plate boundaries). Extending from the shoreline is the generally shallow, low relief, and gently sloping *continental shelf*, which can contain various features such as coastal islands, reefs, and banks. The boundary between the continental slope and the continental shelf is marked by an increase in slope that occurs at the *shelf break*. Cutting deep into the slopes are *submarine canyons*, which resemble canyons on land but are created by erosive turbidity currents. *Turbidity currents* deposit their sediment load at the base of the continental slope, creating deep-sea fans that merge to produce a gently sloping continental rise. The deposits from turbidity currents (called *turbidite deposits*) have characteristic sequences of graded bedding. Active margins have similar features although they are modified by their associated plate boundary.

- The *continental rises* gradually become flat, extensive, deep-ocean *abyssal plains*, which form by *suspension settling* of fine sediment. Poking through the sediment cover of the abyssal plains are numerous *volcanic peaks*, including volcanic islands, seamounts, tablemounts, and abyssal hills. In the Pacific Ocean, where sedimentation rates are low, abyssal plains are not extensively developed, and abyssal hill provinces cover broad expanses of ocean floor.

Along the margins of many continents—especially those around the *Pacific Ring of Fire*—are *deep linear scars called ocean trenches* that are associated with convergent plate boundaries and volcanic arcs.

- The *mid-ocean ridge is a continuous mountain range* that winds through all ocean basins and is entirely *volcanic in origin*. Common features associated with the mid-ocean ridge include a *central rift valley*, *faults and fissures*, *seamounts*, *pillow basalts*, *hydrothermal vents*, *deposits of metal sulfides*, and *unusual life forms*. Segments of the mid-ocean ridge are either *oceanic ridges* if steep with rugged slopes (indicative of slow sea floor spreading) or *oceanic rises* if sloped gently and less rugged (indicative of fast spreading).

- *Long linear zones of weakness—fracture zones and transform faults*—cut across vast distances of ocean floor and *offset the axes of the mid-ocean ridge*. Fracture zones and transform faults are differentiated from one another based on the direction of movement across the feature. *Fracture zones* (an intraplate feature) *have movement in the same direction*, while *transform faults* (a transform plate boundary) *have movement in opposite directions*.

Key Terms

Abyssal hill (p. 88)
Abyssal hill province (p. 88)
Abyssal plain (p. 87)
Active margin (p. 82)
Bathymetry (p. 75)
Black smoker (p. 91)
Continental arc (p. 88)
Continental borderland (p. 83)
Continental margin (p. 81)
Continental rise (p. 85)
Continental shelf (p. 82)
Continental slope (p. 83)
Convergent active margin (p. 82)
Deep-ocean basin (p. 81)
Deep-sea fan (p. 85)
Echo sounder (p. 76)
Fathom (p. 76)
Fracture zone (p. 92)
GLORIA (p. 77)
Graded bedding (p. 85)
Hydrothermal vent (p. 90)
Hypsographic curve (p. 80)
Island arc (p. 88)
Metal sulfide (p. 91)
Mid-ocean ridge (p. 81)
Ocean trench (p. 88)
Oceanic ridge (p. 89)
Oceanic rise (p. 89)
Pacific Ring of Fire (p. 88)
Passive margin (p. 82)
Pillow basalt (p. 90)
Pillow lava (p. 90)
Ping (p. 76)
Precipitate (p. 91)
Precision depth recorder (PDR) (p. 76)
Rift valley (p. 89)
Seabeam (p. 77)
Seaknoll (p. 88)
Sea MARC (p. 77)
Seamount (p. 87)
Seismic reflection profile (p. 80)
Shelf break (p. 82
Sonar (p. 77)
Sounding (p. 75)
Submarine canyon (p. 84)
Submarine fan (p. 85)
Suspension settling (p. 87)
Tablemount (p. 88)
Transform active margin (p. 82)
Transform fault (p. 91)
Turbidite deposit (p. 85)
Turbidity current (p. 85)
Volcanic arc (p. 88)
Warm-water vent (p. 91)
White smoker (p. 91)

Review Questions

1. What is bathymetry?

2. Discuss the development of bathymetric techniques, indicating significant advancements in technology.

3. Describe differences between passive and active continental margins. Be sure to include how these features relate to plate tectonics and include an example of each type of margin.

4. Describe the major features of a passive continental margin: continental shelf, continental slope, continental rise, submarine canyon, and deep-sea fans.

5. Explain how submarine canyons are created.

6. What are some differences between a submarine canyon and an ocean trench?

7. Explain what graded bedding is and how it forms.

8. Describe the process by which abyssal plains are created.

9. Discuss the origin of the various volcanic peaks of the abyssal plains: seamounts, tablemounts, and abyssal hills.

10. Describe characteristics and features of the mid-ocean ridge, including the difference between oceanic ridges and oceanic rises.

11. List and describe the different types of hydrothermal vents.

12. What kinds of unusual life can be found associated with hydrothermal vents? How do these organisms survive?

13. Describe the origin of the three basic types of oceanic islands.

Critical Thinking Exercises

1. Describe what is shown by a hypsographic curve and explain why its shape reflects the presence of active tectonic processes on Earth.

2. In which ocean basin are most ocean trenches found? Use plate tectonic processes to help explain why.

3. Use pictures and words to describe differences between fracture zones and transform faults.

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